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Cryogenics and Radiation Damage

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WHAT happens to solids when they are irradiated? Both physicists and engineers are anxious to obtain more and more information on this subject. To the physicist such knowledge may give additional clues to the verification of theories of the solid state; work in this field started with the discovery of X-rays around 1900. To the engineer such knowledge is an absolute necessity when building reactors where simultaneously neutrons, γ -rays, and many other particles, from electrons to fission fragments, may impair the properties of the fuel elements, their cladding, the structural elements, and the moderator; in this case work has been going on since 1943.

To both of them, clear knowledge of the most elementary phenomena, of the way these phenomena are produced, and of the conditions of their disappearance will be of particular value. Analysis of these features provides the technologist with methods for preventing or repairing the damage.

We will, in a short introduction, summarize how radiation damages a solid and how such defects may be observed. Then we will discuss the recovery of defects in the solid state, with particular emphasis on temperature effects. Low temperature irradiation as well as low temperature measurements will then be shown to be a most efficient tool in this field. However, low temperature properties of room temperature irradiated bodies—thermal and electrical resistivity, etc.—are also very often used; to catalogue all the cases where temperatures below 0°C have been employed for this purpose would need a real encyclopedia of radiation damage, not a short paper.

Radiation damage

We will here neglect ionization effects; the result of a fast particle hitting a solid will then be purely a mechanical one. The energy transferred from the incident particle

having a mass M_1 and an energy E_i to a nucleus of mass M_2 may be as large as

$$E_t = \frac{4M_1 M_2}{(M_1 + M_2)^2} E_i$$

according to classical mechanics.¹ In the case of a neutron

$$E_t = \frac{4}{M_2} E_i$$

If this energy were transferred in a time longer than the vibration period of the lattice, that is to say, assuming a shortest wavelength of about $4 \text{ \AA}$ for the Debye vibrations, in a time longer than about 10^{-12} sec, an energy E_t of about 5 eV would be sufficient to displace an atom from a surface site. This limit, calculated for copper from the heat of sublimation, would rise to ~ 10 eV if the atom which is hit is inside the lattice. The formation of a pair, that is to say an interstitial plus a vacancy, by a slow thermodynamically reversible process, like thermal activation, would require $4 + 1 = 5$ eV. But, because of the high speed of the incident particle, the lattice has no time to relax and therefore the minimum E_d of the energy E_t is about 25 eV. The threshold energies vary from one solid to another, and it should be kept in mind that they are far from having the absolutely definite value of a physical constant.

In any case, most of the particles considered in irradiation have energies substantially larger than the required minimum. For instance, 2 MeV neutrons—met with in nuclear reactors—are able to transfer, in the form of energy of displaced atoms, an energy which for copper is about 33×10^3 eV! Besides the mentioned primary defects, like the interstitial-vacancy pair (Frenkel defect), a large number of other lattice defects will be produced in most irradiation experiments: only electron bombardment will

more definitely focus attention on primary defects; E_i remains around some ten electron-volts when E_i is of the order of 1 MeV.

While considering the secondary defects, it is possible for matter to be transferred down a line of atoms in a sequence of collisions, giving rise to displaced atoms far away from the initial impact. These or other events may cause vacancy-interstitial pairs at more or less large distances one from another or clusters of miscellaneous defects. The so-called thermal spikes are produced because of the rapid release of energy in the lattice, rising locally—among some thousands of atoms—for a short time (some 10^{-11} sec), the temperature well above the melting point. Thermal diffusion is largely responsible for defining the dimensions of the molten zone. Inside the latter, vacancies will be frozen in; outside it, because of the expansion, dislocations are produced. Towards the end of this cascade of defects, 'displacement spikes', a less drastic perturbation than the previous one but of the same general aspect, may be produced.

The precise classification of these defects is far from being achieved. We may notice that, apart from their number, they show the general features of 'classical' defects in solids—vacancies, dislocations, and interstitials. To study them with the best chance of success, it is necessary to recognize them as they are produced by the knock-on. We must therefore collect some data about what is generally known on recovery.

Healing out of defects

The most carefully studied 'non-radiation' defects have been dislocations. Their movement produces the recovery of metals after polygonization and, at higher temperatures, recrystallization restores the virgin properties of the solid. It has long been thought that these processes, depending on thermal agitation, happen only above room temperature. Recently, Albert et al.^{2,3} have shown that aluminium cold-worked at 77° K not only recovers but even recrystallizes at -50° C if it is of extremely high purity (less than 10^{-5} impurities).

About 10 years ago, Hilsch et al.,⁴ by preparing film deposits from the vapour on surfaces cooled to liquid helium temperatures, were already able to show structure changes even below 20° K. For instance, gallium in the primary film has a superconductive transition T_c at 8° K, but after warming to 10° K, T_c falls to 6° K, and after heating at 80° K, down to 1.1° K, the normally observed value; electron diffraction has shown the changes of crystalline structure after these different treatments, under the same conditions. Bismuth, ordinarily non-superconducting, has a superconducting phase with $T_c = 6°$ K before heating at 13° K—or at higher temperatures if impurities such as copper, lithium fluoride, or antimony are present.

More macroscopic changes have been observed by Weil and Conte⁵ who found, in 0.2 micron layers of nickel deposited at 14° K, a 10 per cent decrease of remanent magnetization on heating to 20° K, and a more than 40 per

cent decrease of coercive force after reaching room temperature.

It is therefore evident that even at the lowest temperatures some recovery takes place. Working with neutrons at 4° K, Blewitt et al.⁶ have been able to show in very pure copper a recovery (detected by electrical resistance measurements) even at 7.2° K. Moreover, cold-worked copper at 4° K is 30 per cent more damaged than the same metal in the annealed state; recovery can therefore be suspected to start at even this very low temperature provided the metal is very pure and has few initial defects.

Under these conditions, irradiation and measurement at lowest temperatures become a necessity if knowledge of the elementary damage is required.

General methods for studying defects

Most physical and mechanical properties of solids are sensitive to radiation damage as a perturbation of the lattice regularity. Of course the modification is the more appreciable the less other perturbations, for instance thermal agitation, are present. In this connection measurements of *electrical resistivity* are particularly fruitful when done at very low temperatures. The main results on irradiation have been obtained by studying the residual resistivity and we will therefore discuss this method in a special section. Measurements of *thermal conductivity* at

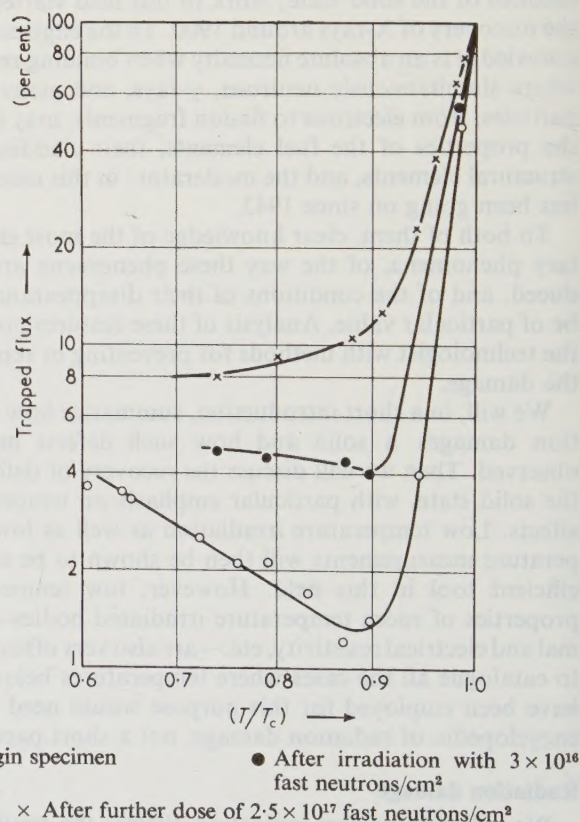


Figure 1. Effect of neutron irradiation on the trapped flux in superconducting rhenium

lowest temperatures may be in some ways more productive because they allow a more detailed theoretical analysis of the nature of defects; in spite of their smaller occurrence in the literature, these measurements will receive special consideration here.

The special case of ionic crystals can be treated by considering the colour centres, even at lowest temperatures. For semiconductors, both Hall effect and resistivity have been very efficient tools.

Measurements of *stored energy*⁶ permit a gross evaluation (a total of some calories per mole) of both damage and recovery temperature; they are just a part of a general problem of low temperature calorimetry.

Specific heat is affected by irradiation; for instance the increase observed in graphite under neutron-bombardment⁷ has been attributed by Goodman et al.⁸ to interstitial atoms between the hexagonal planes.

More recently, Müller⁹ has been able, with an ionic emission microscope and a source at 20° K, to observe directly the vacancies produced by irradiation.

Measurements on superconducting rhenium have given¹⁰ a new approach to damage by means of the effect on frozen flux and transition temperature (see Figure 1).

All the methods we have mentioned, and many others, may be used at the temperature of irradiation, assuming that this temperature is low enough in the cases of resistivity and conductivity (hydrogen or even helium temperature). The high energy brought to the samples by radiation—as we will see below—is a handicap when working under these conditions and until now principally electron or deuteron beams have been used. Often measurements are made at helium or hydrogen temperatures after irradiation or recovery at a higher temperature.

Among the methods specifically limited until recently to room temperature work, it may be interesting to mention direct electron microscopic observation of damage. Hirsch et al.¹¹ found for instance a direct proof of the migration of vacancies in the dislocation loops observed in thinned copper foils irradiated in a nuclear reactor.

These and Müller's observations seem to be the first visible defects; most methods remain deductive, trying by discussing some physical properties to find out what has really happened in the solid.

Electrical resistivity measurements

We will consider only two particular cases that have been studied with this method: tungsten irradiated with neutrons at 4° K,¹² and copper irradiated with electrons at 20° K.¹³ After irradiation, samples are submitted to isochronal heating at successively higher temperatures and the value of $\Delta\rho/\Delta\rho_0$ ($\Delta\rho_0$ being the resistivity increase immediately after damaging) is plotted against the 'annealing' temperature. Figure 2 gives schematic results on tungsten while Figure 3 gives the actual observations on different specimens. It is generally admitted that in the temperature region I, where half of the damage is healed out, interstitials are moving to neighbouring vacancies, and for instance many Frenkel pairs disappear. In stage II,

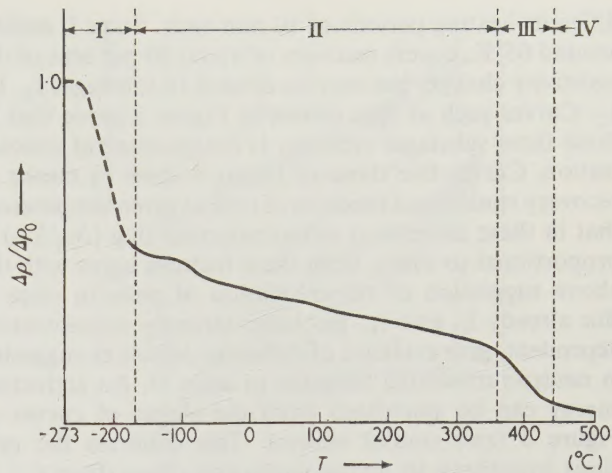


Figure 2. A schematic recovery curve for annealed tungsten after a 140 hr irradiation at 4° K¹²

migration of interstitials in more stable locations occurs, together perhaps with migration of groups of vacancies. In stage III, starting at about 0.2T_f, where T_f is the absolute melting temperature, vacancies become mobile, sometimes leading to the formation of the dislocation loops mentioned above. In stage IV, recrystallization takes place.

A more precise discussion of the electron irradiated copper will now show how the suggested explanations of the different stages have been founded. Let us first recall that electron irradiation at 1.4 MeV merely produces Frenkel defects. Theoretical considerations on experiments show that 1 per cent of displaced atoms produces a resistivity increase of about $1.5 \times 10^{-6} \Omega\text{cm}$. In the present case, the increase of residual resistivity $\Delta\rho_0 = 2.99 \times 10^{-10}$ over the unperturbed copper resistivity (1.5×10^{-9}) is explained by a defect concentration of 2×10^{-6} , a fairly small amount. Figure 4 gives the values of $\Delta\rho/\Delta\rho_0$ after

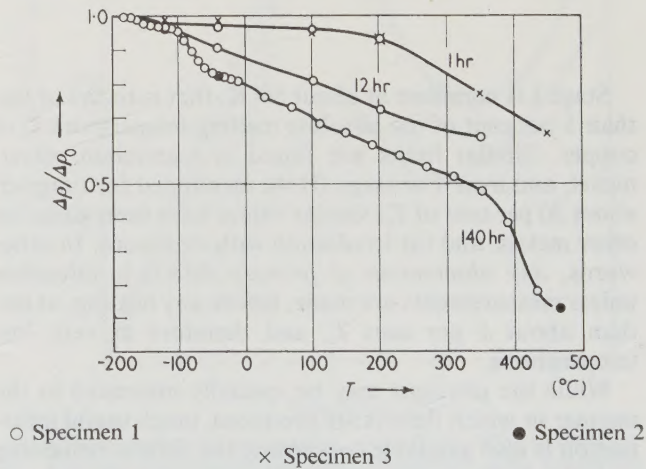


Figure 3. The effect of irradiation time on recovery¹²

different heating periods of 10 min each. Stage I, ending around 65° K, covers recovery of about 90 per cent of the resistivity change, but may be divided in substages I_A, I_B, I_C. Curves such as that shown in Figure 5 prove that in these three substages recovery is independent of concentration. Curves like those of Figure 6 show by means of recovery studies as a function of time at given temperature that in these stages it is monomolecular ($\log(\Delta\rho/\Delta\rho_0)$ is proportional to time). Both these features agree with the above suggestion of recombination of pairs in stage I. But already I_D and I_E, the latter strongly concentration dependent, give evidence of diffusing defects as suggested in neutron irradiated tungsten in stage II. An activation energy can be calculated from the slopes of curves of Figure 6 (and similar curves). This confirms the previous hypothesis by giving increasing values (from 0.1 to 1.0 eV) the more diffusion is involved.

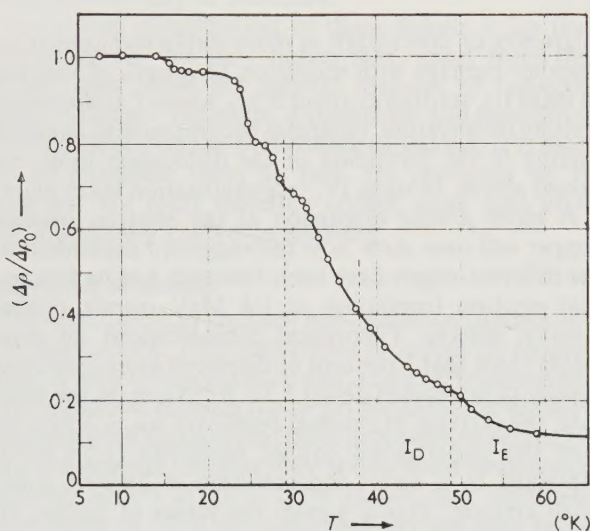


Figure 4

Stage I is complete at about 60° K, that is to say at less than 5 per cent of the absolute melting temperature T_f of copper. Similar limits are found in aluminium, silver, nickel, and iron. For stage III we mentioned for tungsten about 20 per cent of T_f ; similar values have been given for other metals, and for irradiation with deuterons. In other words, any observation of primary defects is infeasible unless measurements are made, before any heating, at less than about 1 per cent T_f , and therefore at very low temperatures.

While the physicist may be specially interested in the manner in which defects are produced, much useful information is also available concerning the defects remaining after the first recovery stages. The following section will give an example of this type of work.

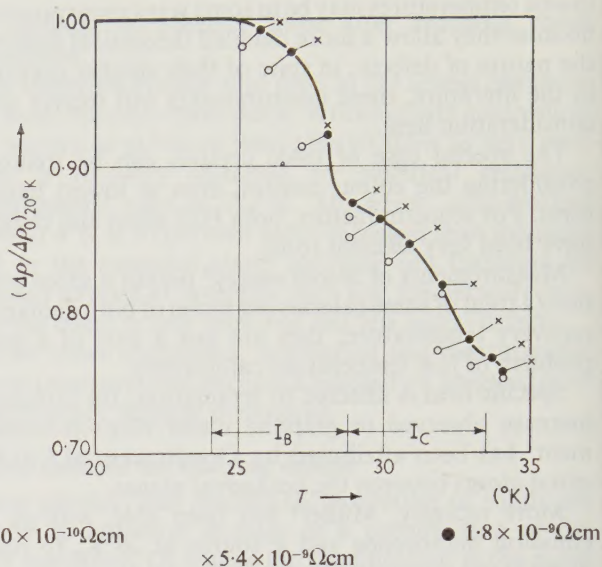


Figure 5

Thermal conductivity at low temperatures

Let us first consider electrically insulating substances. Below the conductivity maximum, K may follow a T^3 law because of the phonon scattering at grain boundaries, a T law because of stacking faults, a T^2 law because of dislocations, a $1/T$ law because of point defects (vacancies as well as isotopes), and a $T^3 \exp(\theta/T)$ law because of the phonon-phonon interactions.

Figure 7 shows some of Berman's¹⁴ results on quartz under neutron-irradiation, varying from $0.05 \times 10^{18} \text{ cm}^{-2}$ to $34.0 \times 10^{18} \text{ cm}^{-2}$, and on silica glass. Even if a quantitative interpretation of the slope on a logarithmic scale

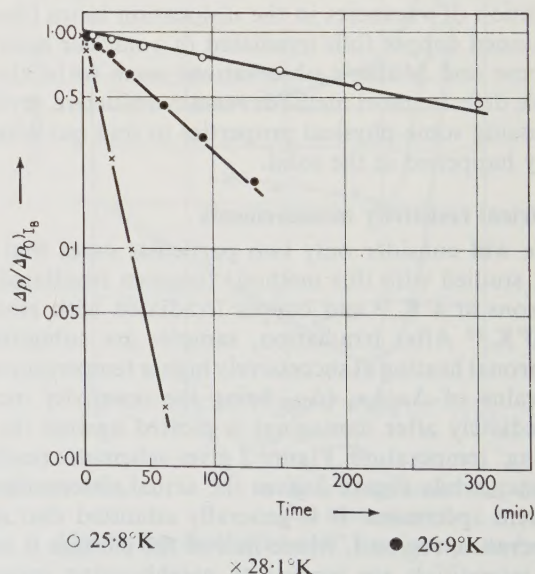
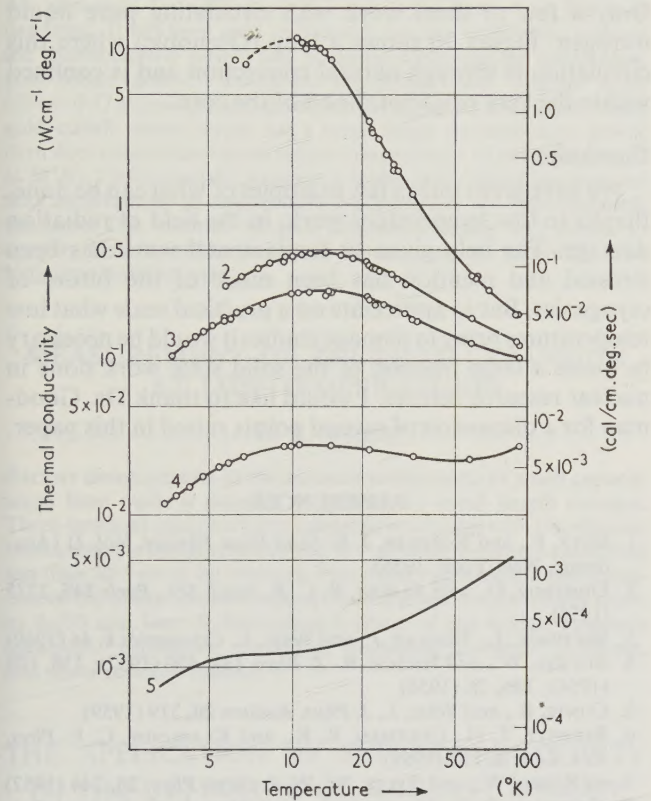


Figure 6

remains difficult, the evolution of the quartz crystal towards the properties of glass is suggestive of the extent of radiation damage.

Mendelssohn,¹⁵ taking advantage of the fact that in superconductors thermal conductivity is only through phonons below $0.2 T/T_c$, could even calculate the number of dislocation lines in niobium strained at helium temperature (Figure 8) following a nearly pure T^2 law (no



1: Quartz crystal, unirradiated 2: After first irradiation 3: After second irradiation 4: After third irradiation 5: Quartz glass

Figure 7. Thermal conductivity of quartz crystal, irradiated quartz crystal, and quartz glass ¹⁴

isotopes present!). He found, for instance, numbers of lines varying from 9.5×10^{10} (at 5 per cent) to 30.0×10^{10} (at 19.5 per cent strain), in fair agreement with what was expected from mechanical considerations. He has now¹⁶ extended this method to irradiated specimens (Figure 9).

Cryogenics of the study of radiation damage

The general conclusion of what we have discussed ought to be that it is necessary, as far as possible, to carry out both the irradiation and the measurements at very low temperatures.

This poses various problems. Even in electron irradiation,¹⁷ where electrons are the only particles hitting the

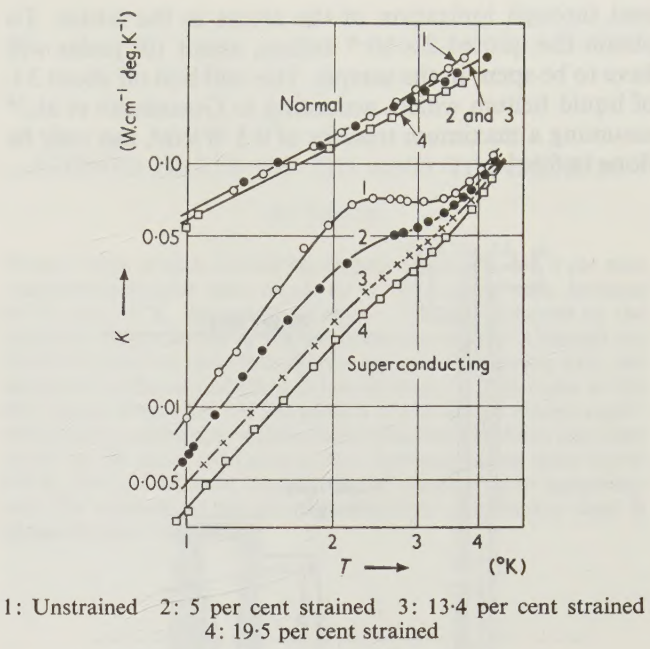


Figure 8. Effect of successive straining of niobium ¹⁵

substance, not all of them are effective in producing displacements. At 1 MeV, with a copper foil of thickness 0.1 mm, only 2 per cent of the electrons produce a defect and the energy of the remaining 98 per cent disappears in

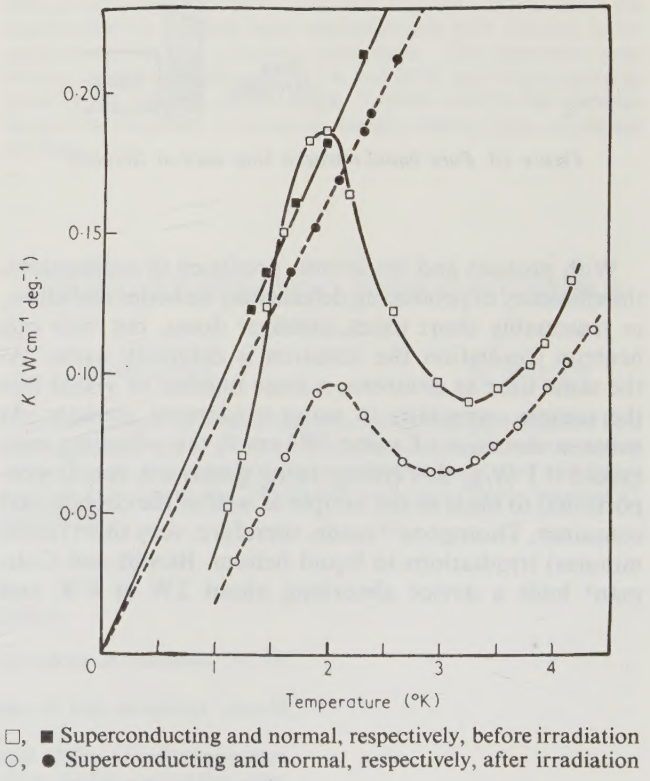


Figure 9. Thermal conductivity of niobium single crystal ¹⁶

heat through ionization of the atoms in the lattice. To obtain the quoted 2×10^{-6} defects, about 10^4 joules will have to be spent in the sample. This will boil off about 3 l. of liquid helium which, according to Grassmann et al.,¹⁸ assuming a maximum transfer of 0.5 W/cm^2 , can only be done in 6 hr!

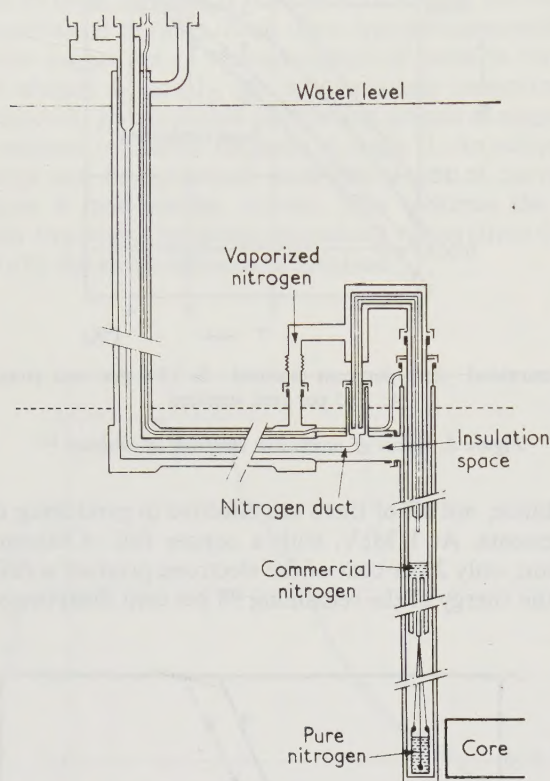


Figure 10. Pure liquid nitrogen loop used at Grenoble

With protons and deuterons, produced in accelerators, the efficiency of producing defects may be better and allow, in reasonably short times, stronger doses, but with pile neutron irradiation the situation is definitely worse. At the same time as neutrons, a large number of γ -rays hits the sample, especially in water moderated reactors. At neutron densities of some 10^{12} cm^{-2} , the γ -heating may exceed 0.1 W/g , this energy being generated, nearly proportional to mass in the sample as well as the coolant and container. Thompson¹² made, therefore, very short (some minutes) irradiations in liquid helium. Blewitt and Colman⁶ built a device absorbing about 2 W at 4°K and

40 W at 9°K for irradiation in the graphite-moderated Oak Ridge reactor, where the neutron flux does not exceed $10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$.

Furthermore, sample, coolant, and container may become radioactive. Under radiation, the coolant, especially if it is impure nitrogen, may be chemically altered; the first nitrogen loops in reactors suffered explosions following build-up of ozone or oxides of nitrogen. Very often, therefore, cold loops in piles are operated at nitrogen temperature with helium gas (Oak Ridge, Brookhaven). Only a few of them work with circulating pure liquid nitrogen. Figure 10 shows a loop (Grenoble) where this circulation is through natural convection and is confined within the very neighbourhood of the core.

Conclusion

We have given only a few examples of what can be done, thanks to low temperature work, in the field of radiation damage. The help given to fundamental work has been stressed and mention has been made of the future of cryogenics. But to appreciate on a practical scale what low temperatures bring to damage studies it would be necessary to quote a large fraction of the solid state work done in nuclear research centres. I would like to thank Dr. Goodman for a discussion of several points raised in this paper.

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Abstracts

LOW TEMPERATURE THERMOCOUPLES—I. GOLD-COBALT OR CONSTANTAN VERSUS COPPER OR 'NORMAL' SILVER

R. L. POWELL M. D. BUNCH R. J. CORRUCINI

AN apparatus for calibrating thermocouples from 4 to 300°K is described. It has been used to obtain a detailed calibration table of the thermoelectric power and potential difference for constantan, gold-cobalt (gold-2.1 atomic per cent cobalt), and 'normal' silver (silver-0.37 atomic per cent gold) versus copper. At low temperatures gold-cobalt versus copper has a much larger thermoelectric power than does constantan versus copper (respectively 16 and 6 $\mu\text{V}/\text{deg.K}$ at 20°K). Unfortunately, however, it is also more inhomogeneous, so that uncertainties in temperature measurement are approximately the same. The 'normal' silver is thermoelectrically very similar to copper. Results are included of inhomogeneity, annealing, and long-time stability tests.

MEASUREMENT OF THERMAL EXPANSION AT LOW TEMPERATURES

G. K. WHITE

RECENT developments in the accurate comparison of small capacitances have made it possible to detect very small length changes. Three-terminal capacitors are compared in a bridge with transformer ratio arms, the bridge sensitivity of 10^{-6} pF allowing length changes of less than 10^{-8} cm to be detected. This makes possible the determination of the linear thermal expansion of solids at temperatures down to $\theta_D/50$ and less. A description is given of the bridge, reference capacitor, 'expansion' capacitor, associated cryogenic problems, and some results obtained.

THE APPLICATION OF SUPERCONDUCTIVITY TO THE DETECTION OF RADIANT ENERGY

D. H. MARTIN

D. BLOOR

THE construction and operation of a detector of radiation which uses the loss of resistance suffered by a superconducting metal on cooling through its transition are described. The minimum detectable signal of the detector is less than 10^{-12} W for a receiving area of 3 mm $\times$ 2 mm and an overall time constant of 1.25 sec. It responds uniformly over the spectrum from the visible and near infra-red to wavelengths exceeding 1 mm. The gain in signal-to-noise ratio over the best thermal detectors operating at room temperature is about $\times 100$.

The theory of operation of the detector, including an analysis of the noise figure of the electrical circuit (parts of which are at 4°K), is given.

ATOMIC HEATS OF TIN AND TIN-INDIUM

M. Yaqub

ATOMIC heats of pure tin and tin-indium alloys of 1 and 2 per cent concentrations have been measured in the normal state between 0.6°K and 1.8°K. Temperatures below 1°K were obtained by the adiabatic magnetization of the specimens themselves. Although the results for pure tin agree remarkably well with the existing data, the agreement in the case of alloys is less satisfactory. This is due to the fact that in alloys a field of 500 gauss is insufficient to suppress superconductivity completely. Atomic heat measurements have also been made for the same specimens in the superconducting state above 0.8°K. For T_c/T between 2 and 4.5 the alloys show better agreement with the exponential law for the electronic contribution than is shown by pure tin.

MULTIPLE LAYER INSULATION FOR CRYOGENIC APPLICATIONS

R. H. KROPSCHOT

THE use of multiple layer insulation for cryogenic applications is discussed. This type of insulation is fabricated by building up layers of a poor conductor (i.e. glass fibre) spaced alternately with a good reflector (i.e. aluminium foil). Results are given for many combinations of insulator and reflector materials. For many applications, the combination of multiple layer insulation and high vacuum is far superior to previous cryogenic insulations. The apparent mean thermal conductivity between 300°K and 20°K for the best samples tested is less than 0.5 $\mu\text{W}/\text{cm.deg.K}$. Typical uses for this material include the insulation of cryogenic vessels, transfer lines, and space vehicles.

A PRESSURE CRYOSTAT WITH CONTINUOUS REFILL

L. BEWILGUA

E. MÜLLER

THE pressure and the level height in a cryostat are kept constant by a simple device. Even under considerable thermal load, measurements of long duration are possible. The cryostat has been used with liquid nitrogen between 78 and 105°K and with liquid argon between 87 and 120°K.

CORRIGENDA

Volume 1, Number 1: *Recent Improvements in Insulants*. A. H. Cockett and W. Molnar.

Page 12, line 6 of Abstract: 'particles of high emissivity' should read 'particles of low emissivity'.

Page 25, Figure 4: Caption should read 'Effect of wall temperature on effective thermal conductivity. Note: broken vertical line refers to wall temperatures of 303 and 77°K'.

Résumés

THERMOCOUPLES A BASSES TEMPERATURES —I. OR-COBALT OU CONSTANTAN ET CUIVRE OU ARGENT 'NORMAL'

R. L. POWELL M. D. BUNCH R. J. CORRUCINI

Les auteurs décrivent un appareil pour l'étalonnage des thermocouples de 4 à 300°K. Ils l'ont utilisé pour établir un tableau d'étalonnage détaillé du pouvoir thermo-électrique et de la force thermo-électrique de couples faits de constantan, d'or-cobalt (2,1 % atom. de cobalt) et d'argent 'normal' (0,37 atomique d'argent pour cent d'or) associés au cuivre. Aux basses températures, l'or-cobalt, associé au cuivre, a un pouvoir thermo-électrique bien plus élevé que le couple constantan cuivre (respectivement 16 et 6 $\mu\text{V}/\text{deg.}$ à 20°K). Malheureusement, il est également plus inhomogène, de sorte que l'incertitude sur les mesures de température est à peu près la même. L'argent 'normal' est analogue au cuivre du point de vue thermo-électrique. L'article donne également les résultats d'essais d'inhomogénéité, de recuite et d'essais de stabilité de longue durée.

MESURE DE LA DILATATION THERMIQUE AUX BASSES TEMPERATURES

G. K. WHITE

Des progrès récents dans le domaine de la comparaison précise des faibles capacités permettent de déceler des changements de longueur très faibles. On compare des condensateurs à trois bornes dans un pont à branches couplées: la sensibilité du pont est de 10^{-6} pF et permet de déceler des variations de longueur de moins de 10^{-8} cm. Il est possible, ainsi, de déterminer la dilatation thermique linéaire de solides à des températures de θ_D 50 et moins. On décrit le pont, le condensateur étalon, le condensateur de 'dilatation', les problèmes cryogéniques connexes et quelques-uns des résultats obtenus.

APPLICATION DE LA SUPRACONDUCTIBILITE A LA DETECTION DE L'ENERGIE RAYONNEE

D. H. MARTIN

D. BLOOR

L'AUTEUR décrit la construction et l'emploi d'un détecteur de radiations qui utilise la disparition de la résistance d'un métal supra-conducteur au passage du point de transition lorsqu'il se refroidit. Le signal minimum décelable par le détecteur est de moins de 10^{-12} W pour un récepteur d'une superficie de 3 mm sur 2 mm, ayant une constante de temps globale de 1,25 sec. Il a une réponse dans tout uniformité au spectre depuis le visible et le proche infra-rouge jusqu'aux longueurs d'ondes dépassant 1 mm. Le gain dans le rapport signal/bruit, est d'environ un facteur 100 par rapport aux meilleurs détecteurs thermiques fonctionnant à la température ambiante.

L'auteur donne la théorie du fonctionnement du détecteur, et en particulier une analyse du bruit du circuit électrique (dont certaines sections sont à 4°K).

CHALEURS ATOMIQUES DE L'ETAIN ET DE L'ETAIN/INDIUM

M. YAQUB

On a mesuré, à l'état normal, entre 0,6°K et 1,8°K, les chaleurs atomiques de l'étain pur et des alliages étain/indium, à concentrations de 1 et 2 pour cent. On a obtenu des températures inférieures à 1°K par aimantation adiabatique des échantillons eux-mêmes. Les résultats obtenus avec l'étain pur s'accordent remarquablement bien avec les données que l'on possède déjà mais, dans le cas des alliages, l'accord est moins satisfaisant. Cela est dû au fait que, dans le cas des alliages, un champ de 500 gauss ne suffit pas pour supprimer complètement la supraconductivité. On a également réalisé des mesures de la chaleur atomique de ces mêmes échantillons à l'état de supra-conducteurs, au dessus de 0,8°K. Lorsque T_C/T se situe entre 2 et 4,5, l'accord avec la loi exponentielle de la contribution électronique est meilleur pour les alliages que pour l'étain pur.

ISOLATION A COUCHES MULTIPLES POUR USAGES CRYOGENIQUES

R. H. KROPSCHOT

L'AUTEUR étudie l'emploi de l'isolation à couches multiples dans les applications cryogéniques. On réalise ce genre d'isolation en plaçant, les unes sur les autres, des couches d'un mauvais conducteur (comme la fibre de verre) séparées entre elles par un bon réflecteur (comme l'aluminium en feuille). L'auteur donne les résultats obtenus avec différentes combinaisons de matériaux isolants et réfléchissants. Dans de nombreux cas, la combinaison d'un isolant à couches multiples et du vide donne des résultats bien supérieurs aux anciens systèmes d'isolation cryogénique. La conductibilité thermique moyenne, de 300°K à 20°K, est de moins de 0,5 $\mu\text{W}/\text{cm. deg. K}$ pour les meilleurs échantillons étudiés. Parmi les applications typiques de cet isolant figurent l'isolement des récipients cryogéniques, des conduits de transport et des véhicules spatiaux.

CRYOSTAT SOUS PRESSION A CHARGEMENT CONTINU

L. BEWILOGUA

E. MÜLLER

Un simple dispositif permet de maintenir la pression et le niveau constants dans un cryostat. Même lorsque le dégagement de chaleur dans le cas est considérable, il est possible d'effectuer des mesures de longue durée. On s'est servi du cryostat avec de l'azote liquide entre 78 et 105°K et avec de l'argon liquide entre 87 et 120°K.

THERMOELEMENTE FÜR TIEFE
TEMPERATUREN—I. GOLD-KOBALT ODER
KONSTANTAN GEGEN KUPFER ODER
'NORMALES' SILBER

R. L. POWELL M. D. BUNCH R. J. CORRUCINI

DER Artikel beschreibt einen Apparat zur Kalibrierung von Thermo-
elementen von 4 bis 300° K. Dieser Apparat wurde zur Erarbeitung
einer ausführlichen Tabelle zur Kalibrierung der Thermokraft und
Potentialdifferenz für Konstantan, Gold-Kobalt (Gold-2,1 Atom-
Prozent Kobalt), und 'normales' Silber (Silber-0,37 Atom-Prozent
Gold) gegen Kupfer. Bei tiefen Temperaturen hat Gold-Kobalt
gegen Kupfer eine viel grössere Thermokraft als Konstantan gegen
Kupfer (16 bzw. 6 $\mu\text{V}/^\circ\text{K}$ bei 20° K). Leider ist es jedoch stärker
inhomogen, sodass die Unsicherheiten bei der Temperaturmessung in
beiden Fällen ungefähr gleich gross sind. 'Normales' Silber ist in
seinen thermoelektrischen Eigenschaften dem Kupfer sehr ähnlich.
Der Artikel enthält auch Resultate von Inhomogenitäts-, Glüh-
und langdauernden Stabilitätstesten.

DIE MESSUNG DER WÄRMEAUSDEHNUNG
BEI TIEFEN TEMPERATUREN

G. K. WHITE

DIE neuesten Entwicklungen im Gebiet des genauen Vergleichs
kleiner Kapazitäten ermöglicht es, ausserordentlich kleine
Längenänderungen festzustellen. Dreiklemmenkondensatoren wer-
den in einer Brücke mit Transformatorübertragungsarmen ver-
glichen, wobei die Empfindlichkeit der Brücke von 10^{-6} pF die
Feststellung von Längenänderungen von weniger als 10^{-8} cm
ermöglicht. Dies gestattet die Bestimmung der linearen Wärmeaus-
dehnung fester Stoffe bis zu Temperaturen von $\theta_D/50$ und darunter.
Der Artikel beschreibt die Brücke, den Bezugskondensator, den
'Expansions' Kondensator, sowie die damit zusammenhängenden
kältetechnischen Probleme und einige Ergebnisse.

DIE ANWENDUNGS VON SUPRALEITFÄHIG-
KEIT ZUR ENTDECKUNG VON STRAHLUNGS-
ENERGIE

D. H. MARTIN

D. BLOOR

DER Artikel bespricht die Konstruktion und den Betrieb eines
Strahlungsdetektors, welcher den Abfall des Widerstands benützt,
den ein supraleitendes Metall beim Abkühlen durch den Sprung-
punkt erleidet. Das kleinste Signal, das vom Detektor entdeckt
werden kann, liegt unter 10^{-12} W für eine Empfangsfläche von
3 mm $\times$ 2 mm und eine Gesamtzeitkonstante von 1,25 sec. Das
Ansprechen erfolgt gleichmässig über das Spektrum vom sichtbaren
und nahen infraroten Bereich bis zu Wellenlängen über 1 mm. Die
Verstärkung des Signal-Geräuschverhältnisses im Vergleich mit den
besten thermischen Detektoren, die bei Zimmertemperatur arbeiten,
beträgt ungefähr das Hundertfache.

Der Artikel enthält auch eine Theorie der Arbeitsweise des
Detektors sowie eine Analyse des Geräuschfaktors des elektrischen
Stromkreises, der teilweise bei 4° K liegt.

DIE ATOMWÄRME VON ZINN UND
ZINN/INDIUM

M. YAQUB

DIE Atomwärmen von reinem Zinn und Zinn-Indium-Legierungen
in Konzentrationen von 1 und 2% wurden im normalen Zustand
zwischen 0,6° K und 1,8° K gemessen. Temperaturen unter 1° K
wurden durch adiabatische Magnetisierung der Proben selbst
erzeugt. Obwohl diese Resultate für reines Zinn sehr gut mit den
vorhandenen Angaben übereinstimmen, ist dies bei den Zinn-
Indium Legierungen weniger der Fall. Dies ist darauf zurück-
zuführen, dass bei den Legierungen ein Feld von 500 Gauss nicht
ausreicht um Supraleitfähigkeit vollkommen zu unterdrücken.
Messungen der Atomwärme wurden für dieselben Proben auch im
Supraleitungszustand über 0,8° K durchgeführt. Für $T_c/T =$
2 bis 4,5 zeigen die Legierungen eine bessere Übereinstimmung
mit dem Exponentialgesetz für den elektronischen Anteil als reines
Zinn.

VIELSCHICHTENISOLIERUNGEN FÜR KÄLTE-
TECHNISCHE ANWENDUNGEN

R. H. KROPSCHOT

DER Artikel bespricht die Anwendung von Vielschichtenisolier-
ungen für kältetechnische Zwecke. Diese Art von Isolierung wird
hergestellt durch Lagen eines schlechten Leiters (z.B. einer Glas-
faser), die voneinander durch einen guten Reflektor (z.B. Alumin-
iumfolie) getrennt sind. Der Artikel bringt die Resultate verschie-
dener Kombinationen von Isolier- und Reflektormaterialien. Für
viele Anwendungen ist die Kombination einer Vielschichtenisolie-
rung mit hohem Vakuum den bisher verwendeten kältetechnischen
Isolierungen bedeutend überlegen. Die scheinbare, durchschnitt-
liche Wärmeleitung der besten Muster zwischen 300° K und 20° K
liegt unter $0,5 \mu\text{W}/\text{cm}^2 \text{ K}$. Typische Anwendungen dieses Materials
umfassen die Isolierung von kältetechnischen Behältern, Über-
tragungsleitungen und Weltraumfahrzeuge.

DRUCK-KRYOSTAT MIT
KONTINUIERLICHER NACHFÜLLUNG

L. BEWILOGUA

E. MÜLLER

IN einem Kryostaten wird auf einfache Weise der Druck und das
Flüssigkeitsniveau konstant gehalten. Damit werden auch bei
beträchtlicher thermischer Belastung lange ununterbrochene
Messdauern möglich. Der Kryostat wurde mit flüssigem Stickstoff
zwischen 78 und 105° K, mit flüssigem Argon zwischen 87 und 120° K
erprobt.

НИЗКОТЕМПЕРАТУРНЫЕ ТЕРМОПАРЫ.—I. ЗОЛОТО-КОБАЛЬТ ИЛИ КОНСТАНТАН ПРОТИВ МЕДИ ИЛИ «НОРМАЛЬНОГО» СЕРЕБРА

R. L. POWELL M. D. BUNCH R. J. CORRUCCINI

Описывается аппарат для калибрования термпар от 4 до 300° K, который применялся для получения подробной калибровочной таблицы термоэлектродвижущей силы и разности потенциалов при константане, золоте-кобальте (золото — 2,1 атомный процент кобальта) и «нормальном» серебре (серебро — 0,37 атомный процент золота) против меди. При низких температурах золото-кобальт против меди обладает гораздо большей термоэлектродвижущей силой чем константан против меди (16 и 6 $\mu\text{V}/^\circ\text{K}$ при 20° K), но к сожалению является также более неомогенным, так что неопределенности при измерении температуры приблизительно одинаковы. «Нормальное» серебро термоэлектрически очень подобно меди. Включаются результаты неомогенности, отжигания и долговременных опытов устойчивости.

ИЗМЕРЕНИЕ ТЕРМИЧЕСКОГО РАСШИРЕНИЯ ПРИ НИЗКИХ ТЕМПЕРАТУРАХ

G. K. WHITE

Последние достижения в аккуратном сравнении маленьких емкостей делают возможным обнаружение очень маленьких изменений длины. Трехзатжимные конденсаторы сравниваются в мостике с трансформаторными плечами; чувствительность мостика 10^{-6} pF позволяет обнаружить изменения длины менее 10^{-8} см. Это делает возможным определение линейного теплового расширения твердых тел при температурах до $\theta_D/50$ и ниже. Описывается мост, эталонный конденсатор, 'расширительный' конденсатор, связанные проблемы криогеники и некоторые полученные результаты.

ПРИМЕНЕНИЕ СВЕРХПРОВОДНОСТИ К ОБНАРУЖЕНИЮ ЛУЧИСТОЙ ЭНЕРГИИ

D. H. MARTIN

D. BLOOR

Описываются конструкция и способ действия детектора излучения основанного на потере сопротивления сверхпроводящего металла по охлаждению через перехода. Минимальный определяемый сигнал детектора менее чем 10^{-12} В при зоне приема сигналов в 3×2 мм и общей постоянной времени 1,25 сек. Детектор реагирует равномерно по спектру от видимого и почти инфракрасного до длин волны больше чем 1 мм. Увеличение отношения сигнал-помеха при наилучших термических детекторах действующих при комнатной температуре — около на 100.

Дается теория действия детектора, включая анализ шумового числа электрической цепи (части которой находятся при 4° K).

АТОМНЫЕ ТЕПЛОЕМКОСТИ ОЛОВА И ОЛОВА/ ИНДИЯ

M. YAQUB

Атомные теплоемкости чистого олова и сплавов олово-индия концентраций 1 и 2 процента измерились в нормальном состоянии между 0,6° K и 1,8° K. Температуры ниже 1° K достиглись путем адиабатической магнетизацией самих проб. Хотя результаты при чистом олове соответствуют прекрасно существующим данным, при сплавах соответствие менее удовлетворительно потому что в сплавах поле 500 единиц гаусс недостаточно для полного подавления сверхпроводимости. Атомная теплоемкость также измерилась при тех же самых пробах в сверхпроводящем состоянии выше 0,8° K. При величинах отношения T_c/T между 2 и 4,5 сплавы показывают лучшее согласие с экспоненциальным законом электронного вклада чем чистое олово.

МНОГОСЛОИСТАЯ ИЗОЛЯЦИЯ ДЛЯ КРИОГЕННЫХ ПРИМЕНЕНИЙ

R. H. KROPSCHOT

Обсуждается употребление многослойной изоляции для криогенных применений. Этот тип изоляции изготовлен возведя слои плохого проводника (т.е. волокна из стекла) с хорошим отражателем (т.е. алюминиевой фольгой) между каждыми двумя слоями. Подаются результаты для много комбинаций изолирующих и отражательных материалов. Для многих применений комбинация многослойной изоляции с высоким вакуумом гораздо лучше чем прежние криогенные изоляции. Видимая средняя теплопроводность между 300° K и 20° K при наилучших испытываемых пробах — ниже чем $0,5 \mu\text{W}/\text{см.град.K}$. Типичными применениями этого материала является изоляция криогенных сосудов, передаточных линий и космических транспортов.

КРИОСТАТ ИЗБЫТОЧНОГО ДАВЛЕНИЯ С НЕПРЕРЫВНОЙ ПОДАЧЕЙ ЖИДКОСТИ

L. BEWILGUA

E. MÜLLER

В криостате обеспечивается простым способом постоянство и давления и уровня жидкости. Этим получается возможность длительной непрерывной работы и при значительной тепловой нагрузке. Криостат испытывался жидким азотом при температурах от 78 до 105° K и жидким аргоном от 87 до 120° K.

Low Temperature Thermocouples—I. Gold-Cobalt or Constantan versus Copper or 'Normal' Silver

R. L. Powell, M. D. Bunch, and R. J. Corruccini
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THE objectives of this research programme were twofold: first, to construct an apparatus for the study and calibration of thermocouples at low temperatures, and, second, to calibrate between 4° and 300° K those commercially available thermocouple wires best suited for low temperature use. In this first report the apparatus is described and data are given on the thermoelectric properties of three alloys, gold-cobalt (gold-2.1 atomic per cent cobalt), constantan, and 'normal' silver (silver-0.37 atomic per cent gold); the special silver-gold alloy is called 'normal' because it was used originally in the Kamerlingh Onnes Laboratory of Leiden University as a laboratory standard or 'normal'. Gold-cobalt was selected because of its large thermoelectric power relative to copper at low temperatures; constantan, because of its widespread use, especially above 90° K. 'Normal' silver is often used instead of copper in systems where heat flow along the thermocouple wires can be troublesome. It has about the same thermoelectric power as copper, but has a much lower thermal conductivity, especially in the liquid hydrogen temperature range. Future reports will contain information on commercial alloys less useful at low temperatures, e.g. chromel, aludel, and iron.

Data on the thermoelectric properties of all three alloys have been published previously. Borelius, Keesom, Johansson, and Linde¹ measured the thermoelectric power of gold-cobalt versus 'normal' silver between 18° and 103° K and at 293° K. More recently, Fuschillo² published a temperature scale for gold-cobalt versus copper from 4° to 300° K and discussed some of the characteristics of the system. A recent book on experimental techniques³ includes graphs of the thermoelectric potential differences of gold-cobalt versus 'normal' silver that were obtained from an unpublished report by Basinski and Swenson. For constantan versus copper thermocouples there is a reference table⁴ from about 670° K down to 85° K, based partly on the low temperature research of Scott.⁵ Calibrations down to 14° K have also been published^{6, 7} for special lots of constantan versus copper thermocouples used for secondary laboratory thermometers. Borelius, Keesom, Johansson, and Linde⁸ measured the thermoelectric power of 'normal' silver versus copper between 17° and 293° K. They also determined the Thomson coefficient, and therefore the

absolute thermoelectric power, of 'normal' silver between 20° and 293° K.⁹ However, previous measurements and calibrations do not provide a satisfactory basis for thermometry at low temperatures because either the temperature range of measurements is not sufficient or the alloys do not correspond closely enough to commercially available alloys.

The low temperature thermal and electrical conductivities of the alloys have also been published; gold-cobalt by Powell, Bunch, and Gibson,¹⁰ constantan by Estermann and Zimmerman¹¹ and others,¹² and 'normal' silver by Grüneisen and Reddemann.¹³

Apparatus

The cryostat shown in Figure 1 consists of two chambers in an evacuated enclosure, the latter immersed in

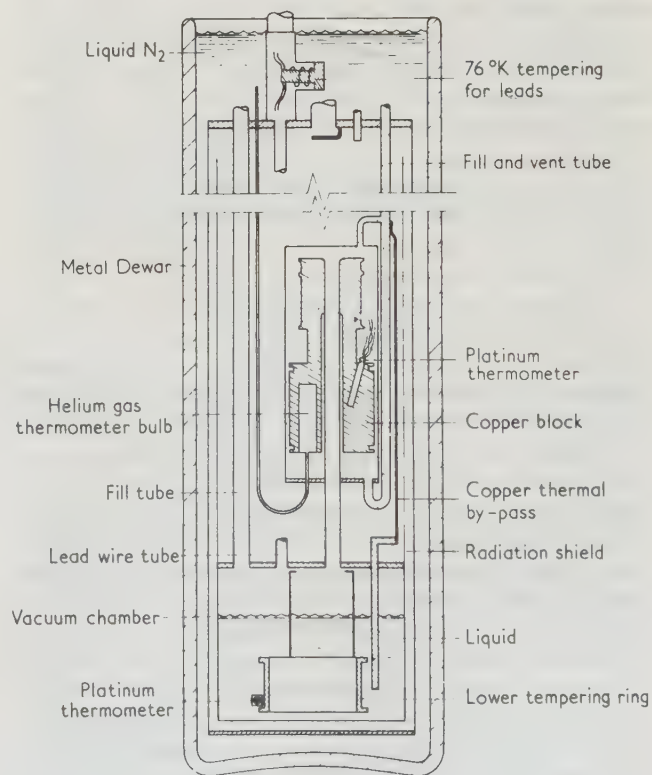


Figure 1. Calibration cryostat

liquid nitrogen. The gas-filled upper chamber contains the variable-temperature junctions of the thermocouples. The lower chamber contains the refrigerant liquid and the reference temperature junctions of the thermocouples.

The important unit in the upper chamber is the copper block. The lower part of the block contains a helium gas thermometer cavity, re-entrant wells for calibrated platinum resistance thermometers, and a groove for the variable-temperature junctions of thermocouples. The thermocouple junctions are soldered to a thin copper plate which is placed between mica sheets and clamped against a plane surface of the groove milled around the block. The upper part of the block has a surface for tempering thermocouple and thermometer wires and for wrapping a block heater. The whole chamber is cooled initially by the introduction of liquid nitrogen, followed by liquid hydrogen or helium when necessary. After evaporation of the last refrigerant, the temperature can be adjusted to any higher value by the electric heater on the uppermost part of the block.

The lower chamber has three functions: (1) it provides nearly constant temperatures for the reference junctions of the thermocouples; (2) it acts as a sink for heat from the warmer surroundings and for heat supplied to hold the upper chamber at elevated temperatures; (3) it is a source of cold vapour which can supply additional refrigeration to the upper chamber when needed. Whenever the two chambers are at nearly the same temperature vapour cooling is required for the upper chamber. The necessary cold vapour is generated by increasing the boiling rate of the refrigerant bath with an electric heater wrapped on the lower chamber. The tempering ring in the lower chamber has a surface for tempering all of the wires and also has holders for a platinum resistance thermometer and for the reference temperature junction of the thermocouples. There is a single reference junction formed by connection of all thermocouple wires to a common lead. The common lead consists of several copper wires in parallel to reduce the effects of local inhomogeneities in the lead wires.

It is important that the upper chamber be isothermal and also that it be thermally isolated from its surroundings, particularly from the warmer areas. To eliminate that heating caused by conduction along the lead wires, all electrical leads from the upper chamber pass through a stainless steel connecting tube to the lower chamber and the refrigerant liquid. From there the wires go up to a tempering rod in thermal contact with liquid nitrogen and then further up to the junction box at room temperature. Thus all heat flowing along the leads from higher temperatures is absorbed in the refrigerant without reaching the upper chamber. Similarly the heat flow down the fill and vent tube of the upper chamber is by-passed to the lower chamber by copper rods connected between the tube and the lower chamber. A large part of the thermal radiation from the walls of the vacuum enclosure is intercepted by a copper shield fastened to the lower chamber. The outside copper wall of the upper chamber

is adjusted to the same temperature as the copper block by means of a heater and a six junction gold-cobalt versus copper differential thermocouple. Thermal gradients within the block are detected by a six junction gold-cobalt versus copper differential thermocouple placed on the upper and lower parts of the block.

Adequate tempering of all thermometer and thermocouple wires is also important for reproducible measurements. In the upper chamber about 1 m of each of the wires is wrapped on the upper part of the block and fastened down with electrical varnish. This brings the wires to the temperature of the block before reaching the thermocouple junctions or thermometer resistance coils. Similarly about 1 m of each wire is wrapped on the tempering ring in the lower chamber.

Because of the large range of temperatures in the upper and lower chambers, temperature measurements are not simple. With liquid helium in the lower chamber, its temperature is determined by reading the barometric pressure and converting to the equivalent temperature by means of the 1958 helium temperature scale.¹⁴ It is not possible to employ this procedure with the nitrogen that we use because of the presence in it of unmeasured small concentrations of argon and oxygen. Therefore a platinum resistance thermometer is used to determine the temperature when the lower chamber contains liquid nitrogen. With liquid hydrogen either procedure can be used. However, it is more convenient to rely on the platinum thermometer because the use of the vapour pressure relations with hydrogen requires a simultaneous analysis of the *ortho-para* composition.¹⁵ The latter method is occasionally used as a check on the platinum thermometer. The *ortho-para* composition, as determined by a gas thermal conductivity analyser, is usually between 88 and 98 per cent *para*-hydrogen.

The temperature of the copper block in the upper chamber is determined with the platinum resistance thermometer if it is between 15° and 300° K and with the constant volume helium gas thermometer if it is between 4° and 25° K. In order to determine the pressure within the gas thermometer, the cavity is connected to a mercury manometer by 580 cm of 0.015 in. i.d. capillary tubing. The glass tubing of the manometer has a diameter of 10 mm. The gas thermometer cavity of volume 50 cm³ is initially filled with pure helium to a pressure of 20 cm Hg while the block is held at a temperature of about 20° K. The height of the mercury in the manometer is read to better than 0.1 mm (equivalent to 0.01° K) with a precision cathetometer.

The capsule type resistance thermometers, calibrated by the National Bureau of Standards at Washington,¹⁶ are measured with a Mueller bridge. The precision of measurement is equivalent to about 0.001° K above 15° K. The thermocouple potentials are measured to about 0.01 μ V with a six decade potentiometer. A breaker amplifier with phase sensitive detection and a filtered output meter serves as the null indicator for both the bridge and the potentiometer.

Samples

All of the thermocouple wires were calibrated in the condition in which they were received from the manufacturer. The gold-cobalt and 'normal' silver had been hard-drawn to a diameter of 0.005 in. from a bar of about 1 in. diameter. They were both covered with a woven glass fibre insulation, but were not varnished. The constantan wires were 36 A.w.g. (0.005 in. diameter), 'Teflon' covered, I.S.A. code TN. The gold-cobalt, labelled Bar 5, and 'normal' silver were obtained from Sigmund Cohn Corporation, Mt Vernon, New York; the constantan, from Thermo Electric Inc., Saddle Brook, New Jersey. The reference metal and extension wires were instrument grade copper obtained from Leeds and Northrup Co., Philadelphia, Pennsylvania.

The apparatus was designed to contain up to twelve thermocouples for concurrent testing. For this report there were eleven: four gold-cobalt, four constantan, and three 'normal' silver, numbered respectively 1-4, 5-8, and 9-11.

Performance

The apparatus requires 6 l. of liquid helium to cool it down from 20° to 4° K and to fill the lower chamber. The rate of use after that varies from 0.25 to 1.0 l./hr, depending on the temperature in the upper chamber. With liquid hydrogen or nitrogen the problem of boil-off is much less serious. Even with the largest gradients, liquid hydrogen will remain in the lower chamber for over 6 hr. The time required to change temperatures in the upper chamber and to re-establish equilibrium is about 1 hr.

Consideration of all sources of error, exclusive of those inherent in the thermocouple materials, suggests that temperatures can be realized and measured with an accuracy of about 0.02° K and that thermoelectric potentials can be measured with a reproducibility of about 0.01 μV below 1 mV and about 0.1 μV for higher values. Temperature differences between the top and bottom of the copper block in the upper chamber are always less than 0.01° K during an equilibrium period. The temperature of the outer wall of the upper chamber is regularly held to within 0.1° K of the copper block. Insufficient tempering of the thermocouple and thermometer wires would allow errors caused by heat conduction across the junctions. This would in turn cause inconsistencies in the readings for temperature ranges that overlap each other. There is no clear indication of a significant error caused by this possible difficulty.

The systematic and instrumentation errors mentioned above are normally outweighed by the inhomogeneity variations characteristic of thermocouple wires. This was especially true for the gold-cobalt material. In the first experiments with the calibration apparatus, the data for gold-cobalt versus copper had much greater scatter than that for constantan versus copper. This was caused by a varying liquid level in the lower chamber, which had the

effect of altering the temperature gradients on the wires in regions having inhomogeneities. With gold-cobalt versus copper, there were thermoelectric potential variations of up to 5 μV with liquid hydrogen and of up to 20 μV with liquid nitrogen when the liquid level changed by several centimetres. The constantan versus copper thermocouples had almost negligible changes in the same experiments. Thereafter the liquid level was held constant to within about 0.5 cm in order to improve the consistency of the data. The effects of inhomogeneities are discussed further in the section on results.

Analysis of data

Numerous corrections to a manometer reading are necessary before the true gas thermometer temperature can be obtained. First, conventional corrections for temperature, gravitational field, and meniscus height of the mercury manometer must be made.¹⁷ Then, corrections to the gas thermometer pressure must be calculated to account for nuisance volumes, density of the transmitting column of helium, thermo-molecular effect in the helium, and for the deviations from ideality of the helium gas.^{18, 19} The corrections for the non-ideality of helium are by far the largest; as large as 0.05° K near 20° K. By contrast, the corrections to a platinum resistance thermometer reading are quite simple.

Treatment of the corrected data is complicated by the use of three different reference junction temperatures at approximately 4°, 20°, and 76° K. The procedure consists of (1) fitting by least squares of semi-empirical expressions to the data for each temperature range, (2) computing of smooth tables of values from the equations for a given thermocouple, and (3) adjusting by very small amounts the slopes at 20° and 76° K where different sets of computed values join.

For gold-cobalt versus copper between 4° and 25° K the reference junction was at about 4° K and the equation used for fitting was

E_T - E_4 = A + BT^2 + CT^3 ... (1)

Since

E_4 - E_0 = -A,

the values of thermoelectric potential differences for a reference temperature at 0° K could be calculated from

E_T - E_0 = BT^2 + CT^3 ... (2)

Measurements with a reference junction temperature at about 20° K were adjusted to a reference at 0° K by adding the quantity E_20 - E_0, as calculated from equation (2). The adjusted values were fitted to the equation

T^2 / (E_T - E_0) = D + ET + FT^2 ... (3)

The same procedure was repeated for measurements with a reference junction temperature at about 76° K.

The data for constantan versus copper were treated similarly except that values above 150° K were separately

fitted by a cubic equation in temperature. The thermoelectric potential differences for 'normal' silver versus copper were small and therefore were smoothed and interpolated graphically.

The final representative reference table for a thermocouple combination was obtained by averaging the values for all of the separate thermocouples of the specified materials.

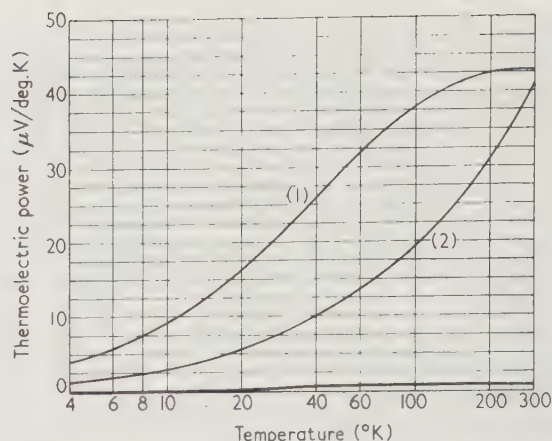
Results and discussion

Smoothed average data for the thermoelectric potential differences and powers of gold-cobalt, constantan, and 'normal' silver versus copper are given in Figure 2 and Tables 1, 2, and 3. Deviations of the thermoelectric potential differences for each thermocouple from the smoothed average values for all thermocouples of the same type are given in Figures 3, 4, and 5. The deviations plotted indicate the total differences to be expected between wires from the same lot.

The relative deviations of the thermoelectric powers for wires from a single lot of constantan are about 0.3 per cent up to 20° K, 0.03 per cent from 20° to 80° K, and 0.02 per cent from 80° to 300° K. With gold-cobalt the deviations are much larger for most of the temperature range: 0.5 per cent below 20° K, 0.3 per cent above. For both alloys the deviations between wires from the same lot could represent significant errors in temperature determinations if low temperature measurements were made with ice point reference junctions. This is especially true for gold-cobalt because of its large relative deviations at higher temperatures. 'Normal' silver has relative deviations of about 1 per cent over the entire temperature range. The absolute deviations of 'normal' silver are, however, very small, from 0.1 to 1 μ V.

The deviations between wires from different lots are much greater than the deviations within one lot, especially for gold-cobalt. Earlier runs on gold-cobalt versus copper at this laboratory gave values up to 5 per cent lower than the ones given in Table 1.²⁰ More recent spot-checks on current lots of wire are up to 1 per cent lower than those values. The results of Fuschillo² are from 8 to 17 per cent lower than ours; those of Borelius et al.¹ are from 0.3 to 10 per cent higher. The relative deviations are greatest below 20° K and above 200° K; the intermediate range seems to be more reproducible. The results of Borelius et al.⁸ on 'normal' silver versus copper are about the same as ours at lower temperatures, but up to 25 per cent lower near room temperatures.

The deviations between the constantan versus copper thermocouples reported in this paper and those given in *N.B.S. Circular 561*⁴ are quite small, never more than 1 per cent above 80° K, the lower limit of the *N.B.S. Circular* tables. The results of Giauque, Buffington, and Schulze,⁶ and Aston, Willihnganz, and Messerly,⁷ differ considerably from those given here, from 3 to 7 per cent and 4 to 20 per cent respectively. The largest variations were at the higher temperatures. A lot of commercial thermocouple constantan tested here earlier differed from



(1) Au-2.1% (at) Co versus Cu (2) Constantan versus Cu
(3) Ag-0.37% (at) Au versus Cu

Figure 2. Thermoelectric power of gold-cobalt, constantan, and 'normal' silver versus copper

the present results by 0.5 to 3 per cent, with the largest variations being at the lower temperatures.

Auxiliary measurements were also carried out on gold-cobalt to determine the effects of time variations (room temperature ageing or annealing) and of higher temperature anneals. Three thermocouples were tested over a period of 2.5 years. One of them had no significant decrease in thermoelectric power, one decreased 3 per cent, and one 5 per cent. For the latter two, approximately a 1 per cent change occurred in the first 6 months. The annealing tests showed that a 24 hr anneal did not change the thermoelectric power significantly if the annealing temperature was below 70° C. At 90° C a 24 hr anneal decreased the thermoelectric power about 1 per cent. The decrease in thermoelectric power caused by both the ageing at room temperature and the annealing at slightly elevated temperatures probably reflected changes in chemical composition within the crystallites.

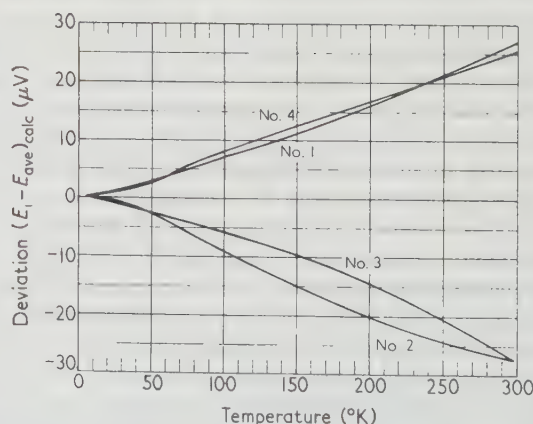


Figure 3. Deviations of individual gold-cobalt versus copper thermocouples from the group average

Table 1. Gold-2:1 Atomic Per Cent Cobalt versus Copper Thermocouples

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
1	0.53	0.53	1.047	56	1076.2	31.1	31.183
2	2.09	1.56	2.070	57	1107.5	31.3	31.430
3	4.66	2.57	3.069	58	1139.1	31.6	31.671
4	8.22	3.56	4.044	59	1170.9	31.8	31.905
5	12.74	4.52	4.994	60	1202.9	32.0	32.134
6	18.20	5.46	5.920	61	1235.1	32.2	32.356
7	24.57	6.37	6.822	62	1267.6	32.5	32.573
8	31.83	7.26	7.700	63	1300.3	32.7	32.784
9	39.96	8.13	8.554	64	1333.1	32.9	32.989
10	48.93	8.97	9.383	65	1366.2	33.1	33.189
11	58.72	9.79	10.188	66	1399.5	33.3	33.384
12	69.30	10.58	10.969	67	1433.0	33.5	33.574
13	80.65	11.35	11.726	68	1466.7	33.7	33.758
14	92.75	12.09	12.459	69	1500.5	33.8	33.938
15	105.6	12.8	13.167	70	1534.5	34.0	34.112
16	119.1	13.5	13.847	71	1568.7	34.2	34.282
17	133.2	14.2	14.513	72	1603.1	34.4	34.442
18	148.1	14.8	15.165	73	1637.6	34.5	34.599
19	163.5	15.5	15.803	74	1672.3	34.7	34.753
20	179.6	16.1	16.428	75	1707.1	34.8	34.906
21	196.4	16.7	17.038	76	1742.1	35.0	35.056
22	213.7	17.3	17.635	77	1777.2	35.1	35.205
23	231.6	17.9	18.218	78	1812.5	35.3	35.351
24	250.1	18.5	18.791	79	1847.9	35.4	35.497
25	269.1	19.1	19.349	80	1883.5	35.6	35.640
26	288.8	19.6	19.893	81	1919.2	35.7	35.783
27	308.9	20.2	20.424	82	1955.0	35.9	35.929
28	329.6	20.7	20.941	83	1991.0	36.0	36.072
29	350.8	21.2	21.446	84	2027.2	36.1	36.211
30	372.5	21.7	21.937	85	2063.4	36.3	36.349
31	394.7	22.2	22.417	86	2099.9	36.4	36.483
32	417.3	22.7	22.884	87	2136.4	36.5	36.615
33	440.4	23.1	23.340	88	2173.1	36.7	36.744
34	464.0	23.6	23.785	89	2209.9	36.8	36.871
35	488.0	24.0	24.218	90	2246.8	36.9	36.995
36	512.4	24.4	24.640	91	2283.9	37.1	37.117
37	537.3	24.8	25.052	92	2321.1	37.2	37.236
38	562.5	25.3	25.454	93	2358.4	37.3	37.353
39	588.2	25.7	25.846	94	2395.8	37.4	37.468
40	614.2	26.0	26.228	95	2433.3	37.5	37.581
41	640.6	26.4	26.600	96	2470.9	37.6	37.692
42	667.4	26.8	26.963	97	2508.7	37.7	37.800
43	694.6	27.1	27.317	98	2546.5	37.9	37.907
44	722.1	27.5	27.662	99	2584.5	38.0	38.011
45	749.9	27.8	27.998	100	2622.6	38.1	38.113
46	778.1	28.2	28.326	101	2660.7	38.2	38.214
47	806.5	28.5	28.646	102	2699.0	38.3	38.312
48	835.3	28.8	28.958	103	2737.3	38.4	38.409
49	864.5	29.1	29.261	104	2775.8	38.5	38.504
50	893.9	29.4	29.558	105	2814.4	38.6	38.597
51	923.6	29.7	29.846	106	2853.0	38.6	38.689
52	953.6	30.0	30.127	107	2891.7	38.7	38.778
53	983.8	30.3	30.402	108	2930.6	38.8	38.866
54	1014.4	30.5	30.669	109	2969.5	38.9	38.953
55	1045.2	30.8	30.929	110	3008.5	39.0	39.038

Table 1 (continued)

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
111	3047.5	39.1	39.121	166	5290.3	41.9	41.959
112	3086.7	39.2	39.202	167	5332.3	42.0	41.988
113	3125.9	39.2	39.283	168	5374.3	42.0	42.016
114	3165.3	39.3	39.361	169	5416.4	42.0	42.044
115	3204.7	39.4	39.439	170	5458.4	42.1	42.072
116	3244.1	39.5	39.514	171	5500.5	42.1	42.099
117	3283.7	39.6	39.589	172	5542.6	42.1	42.125
118	3323.3	39.6	39.662	173	5584.7	42.1	42.151
119	3363.0	39.7	39.733	174	5626.9	42.2	42.176
120	3402.8	39.8	39.804	175	5669.1	42.2	42.201
121	3442.6	39.8	39.873	176	5711.3	42.2	42.225
122	3482.5	39.9	39.941	177	5753.5	42.2	42.249
123	3522.5	40.0	40.007	178	5795.8	42.3	42.272
124	3562.5	40.0	40.073	179	5838.1	42.3	42.295
125	3602.6	40.1	40.137	180	5880.4	42.3	42.317
126	3642.8	40.2	40.200	181	5922.7	42.3	42.339
127	3683.0	40.2	40.262	182	5965.1	42.3	42.360
128	3723.3	40.3	40.322	183	6007.4	42.4	42.381
129	3763.7	40.4	40.382	184	6049.8	42.4	42.402
130	3804.1	40.4	40.440	185	6092.2	42.4	42.422
131	3844.6	40.5	40.498	186	6134.7	42.4	42.441
132	3885.1	40.5	40.554	187	6177.1	42.5	42.460
133	3925.7	40.6	40.609	188	6219.6	42.5	42.479
134	3966.3	40.6	40.664	189	6262.1	42.5	42.497
135	4007.0	40.7	40.717	190	6304.6	42.5	42.515
136	4047.7	40.7	40.769	191	6347.1	42.5	42.533
137	4088.5	40.8	40.821	192	6389.7	42.5	42.550
138	4129.4	40.8	40.871	193	6432.2	42.6	42.567
139	4170.3	40.9	40.921	194	6474.8	42.6	42.583
140	4211.2	40.9	40.969	195	6517.4	42.6	42.599
141	4252.2	41.0	41.017	196	6560.0	42.6	42.615
142	4293.3	41.0	41.064	197	6602.6	42.6	42.630
143	4334.3	41.1	41.110	198	6645.3	42.6	42.645
144	4375.5	41.1	41.155	199	6687.9	42.7	42.660
145	4416.7	41.2	41.199	200	6730.6	42.7	42.674
146	4457.9	41.2	41.243	201	6773.3	42.7	42.688
147	4499.1	41.3	41.285	202	6815.9	42.7	42.701
148	4540.4	41.3	41.327	203	6858.7	42.7	42.714
149	4581.8	41.3	41.368	204	6901.4	42.7	42.727
150	4623.2	41.4	41.408	205	6944.1	42.7	42.740
151	4664.6	41.4	41.448	206	6986.9	42.7	42.752
152	4706.1	41.5	41.487	207	7029.6	42.8	42.764
153	4747.6	41.5	41.525	208	7072.4	42.8	42.775
154	4789.1	41.5	41.562	209	7115.2	42.8	42.786
155	4830.7	41.6	41.599	210	7158.0	42.8	42.797
156	4872.3	41.6	41.635	211	7200.8	42.8	42.808
157	4914.0	41.7	41.670	212	7243.6	42.8	42.818
158	4955.7	41.7	41.705	213	7286.4	42.8	42.828
159	4997.4	41.7	41.739	214	7329.2	42.8	42.838
160	5039.1	41.8	41.772	215	7372.1	42.8	42.848
161	5080.9	41.8	41.805	216	7414.9	42.9	42.857
162	5122.8	41.8	41.837	217	7457.8	42.9	42.866
163	5164.6	41.9	41.868	218	7500.7	42.9	42.874
164	5206.5	41.9	41.899	219	7543.5	42.9	42.883
165	5248.4	41.9	41.929	220	7586.4	42.9	42.891

Table 1 (continued)

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/\text{deg. K}$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/\text{deg. K}$)
221	7629.3	42.9	42.899	261	9349.0	43.0	43.031
222	7672.2	42.9	42.906	262	9392.0	43.0	43.031
223	7715.1	42.9	42.913	263	9435.0	43.0	43.030
224	7758.0	42.9	42.920	264	9478.1	43.0	43.029
225	7801.0	42.9	42.927	265	9521.1	43.0	43.028
226	7843.9	42.9	42.934	266	9564.1	43.0	43.027
227	7886.8	42.9	42.940	267	9607.2	43.0	43.026
228	7929.8	42.9	42.946	268	9650.2	43.0	43.025
229	7972.7	42.9	42.952	269	9693.2	43.0	43.023
230	8015.7	43.0	42.958	270	9736.2	43.0	43.022
231	8058.6	43.0	42.963	271	9779.2	43.0	43.020
232	8101.6	43.0	42.968	272	9822.3	43.0	43.018
233	8144.6	43.0	42.973	273	9865.3	43.0	43.016
234	8187.6	43.0	42.978	274	9908.3	43.0	43.014
235	8230.5	43.0	42.982	275	9951.3	43.0	43.011
236	8273.5	43.0	42.987	276	9994.3	43.0	43.009
237	8316.5	43.0	42.991	277	10037.3	43.0	43.006
238	8359.5	43.0	42.995	278	10080.3	43.0	43.004
239	8402.5	43.0	42.998	279	10123.3	43.0	43.001
240	8445.5	43.0	43.002	280	10166.3	43.0	42.998
241	8488.5	43.0	43.005	281	10209.3	43.0	42.995
242	8531.5	43.0	43.008	282	10252.3	43.0	42.992
243	8574.5	43.0	43.011	283	10295.3	43.0	42.988
244	8617.5	43.0	43.014	284	10338.3	43.0	42.985
245	8660.5	43.0	43.016	285	10381.3	43.0	42.981
246	8703.6	43.0	43.018	286	10424.3	43.0	42.978
247	8746.6	43.0	43.020	287	10467.2	43.0	42.974
248	8789.6	43.0	43.022	288	10510.2	43.0	42.970
249	8832.6	43.0	43.024	289	10553.2	43.0	42.966
250	8875.6	43.0	43.026	290	10596.1	43.0	42.962
251	8918.7	43.0	43.027	291	10639.1	43.0	42.958
252	8961.7	43.0	43.028	292	10682.1	43.0	42.953
253	9004.7	43.0	43.029	293	10725.0	43.0	42.949
254	9047.8	43.0	43.030	294	10768.0	42.9	42.944
255	9090.8	43.0	43.031	295	10810.9	42.9	42.940
256	9133.8	43.0	43.031	296	10853.8	42.9	42.935
257	9176.9	43.0	43.031	297	10896.8	42.9	42.930
258	9219.9	43.0	43.032	298	10939.7	42.9	42.925
259	9262.9	43.0	43.032	299	10982.6	42.9	42.920
260	9305.9	43.0	43.031	300	11025.5	42.9	42.915

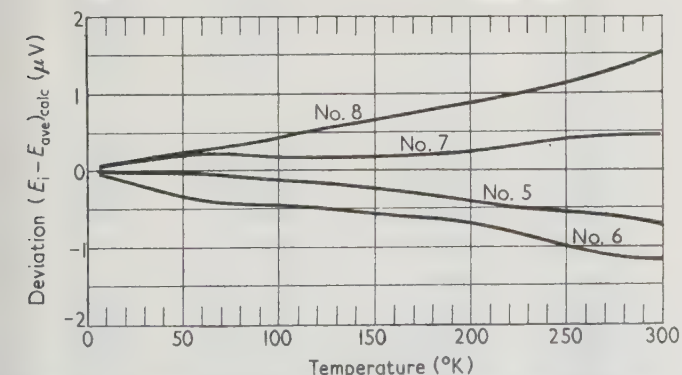


Figure 4. Deviations of individual constantan versus copper thermocouples from the group average

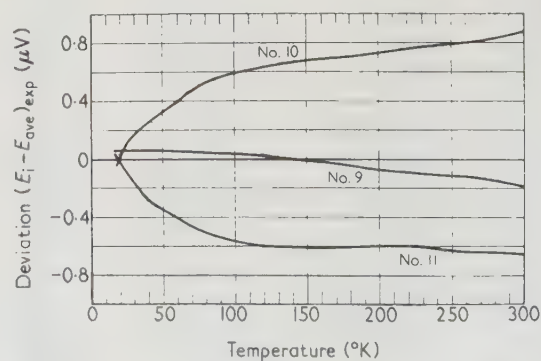


Figure 5. Deviations of individual 'normal' silver versus copper thermocouples from the group average

Table 2. Constantan versus Copper Thermocouples

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
1	0.17	0.17	0.331	56	411.9	13.2	13.236
2	0.66	0.49	0.657	57	425.2	13.3	13.401
3	1.48	0.82	0.979	58	438.7	13.5	13.564
4	2.62	1.14	1.295	59	452.4	13.6	13.726
5	4.07	1.45	1.607	60	466.2	13.8	13.885
6	5.83	1.76	1.915	61	480.1	14.0	14.043
7	7.90	2.07	2.217	62	494.3	14.1	14.199
8	10.26	2.37	2.515	63	508.5	14.3	14.353
9	12.92	2.66	2.808	64	523.0	14.4	14.505
10	15.88	2.95	3.097	65	537.5	14.6	14.655
11	19.12	3.24	3.380	66	552.3	14.7	14.804
12	22.64	3.52	3.659	67	567.2	14.9	14.950
13	26.43	3.80	3.934	68	582.2	15.0	15.095
14	30.50	4.07	4.203	69	597.3	15.2	15.239
15	34.84	4.34	4.468	70	612.7	15.3	15.380
16	39.43	4.59	4.728	71	628.1	15.5	15.520
17	44.29	4.86	4.988	72	643.7	15.6	15.651
18	49.40	5.11	5.248	73	659.4	15.7	15.780
19	54.78	5.37	5.508	74	675.3	15.8	15.907
20	60.40	5.63	5.765	75	691.2	16.0	16.032
21	66.28	5.88	6.019	76	707.3	16.1	16.156
22	72.42	6.13	6.269	77	723.5	16.2	16.290
23	78.80	6.38	6.517	78	739.9	16.4	16.424
24	85.43	6.63	6.761	79	756.4	16.5	16.556
25	92.31	6.88	7.003	80	773.0	16.6	16.688
26	99.43	7.12	7.242	81	789.8	16.8	16.819
27	106.8	7.4	7.478	82	806.6	16.9	16.958
28	114.4	7.6	7.711	83	823.7	17.0	17.095
29	122.2	7.8	7.942	84	840.8	17.2	17.232
30	130.3	8.1	8.170	85	858.1	17.3	17.369
31	138.6	8.3	8.395	86	875.6	17.4	17.505
32	147.1	8.5	8.617	87	893.1	17.6	17.640
33	155.8	8.7	8.837	88	910.9	17.7	17.775
34	164.7	8.9	9.054	89	928.7	17.8	17.909
35	173.9	9.2	9.269	90	946.7	18.0	18.043
36	183.3	9.4	9.481	91	964.8	18.1	18.176
37	192.9	9.6	9.691	92	983.0	18.2	18.309
38	202.7	9.8	9.898	93	1001.4	18.4	18.441
39	212.7	10.0	10.103	94	1019.9	18.5	18.573
40	222.9	10.2	10.305	95	1038.5	18.6	18.705
41	233.3	10.4	10.505	96	1057.3	18.8	18.836
42	243.9	10.6	10.702	97	1076.2	18.9	18.967
43	254.7	10.8	10.898	98	1095.2	19.0	19.097
44	265.7	11.0	11.091	99	1114.4	19.2	19.227
45	276.8	11.2	11.281	100	1133.7	19.3	19.357
46	288.2	11.4	11.470	101	1153.1	19.4	19.486
47	299.8	11.6	11.656	102	1172.7	19.6	19.615
48	311.5	11.7	11.840	103	1192.4	19.7	19.744
49	323.5	11.9	12.022	104	1212.2	19.8	19.873
50	335.6	12.1	12.201	105	1232.1	19.9	20.001
51	347.9	12.3	12.379	106	1252.2	20.1	20.129
52	360.3	12.5	12.554	107	1272.4	20.2	20.257
53	373.0	12.6	12.728	108	1292.7	20.3	20.384
54	385.8	12.8	12.899	109	1313.1	20.4	20.511
55	398.8	13.0	13.068	110	1333.7	20.6	20.639

Table 2 (continued)

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
111	1354.4	20.7	20.765	166	2686.0	27.5	27.560
112	1375.2	20.8	20.892	167	2713.6	27.6	27.675
113	1396.2	21.0	21.019	168	2741.3	27.7	27.791
114	1417.3	21.1	21.145	169	2769.2	27.8	27.906
115	1438.5	21.2	21.272	170	2797.1	28.0	28.022
116	1459.8	21.3	21.398	171	2825.2	28.1	28.137
117	1481.3	21.5	21.524	172	2853.4	28.2	28.251
118	1502.9	21.6	21.650	173	2881.7	28.3	28.366
119	1524.6	21.7	21.775	174	2910.1	28.4	28.480
120	1546.4	21.8	21.901	175	2938.7	28.5	28.594
121	1568.4	22.0	22.027	176	2967.3	28.7	28.708
122	1590.5	22.1	22.153	177	2996.1	28.8	28.822
123	1612.7	22.2	22.278	178	3025.0	28.9	28.935
124	1635.0	22.3	22.404	179	3054.0	29.0	29.048
125	1657.5	22.5	22.529	180	3083.1	29.1	29.161
126	1680.1	22.6	22.655	181	3112.3	29.2	29.274
127	1702.8	22.7	22.780	182	3141.6	29.3	29.387
128	1725.6	22.8	22.905	183	3171.1	29.4	29.499
129	1748.6	23.0	23.031	184	3200.6	29.6	29.611
130	1771.7	23.1	23.156	185	3230.3	29.7	29.723
131	1794.9	23.2	23.282	186	3260.1	29.8	29.834
132	1818.3	23.3	23.407	187	3290.0	29.9	29.946
133	1841.7	23.5	23.533	188	3320.0	30.0	30.057
134	1865.3	23.6	23.659	189	3350.1	30.1	30.168
135	1889.1	23.7	23.784	190	3380.3	30.2	30.278
136	1912.9	23.8	23.910	191	3410.6	30.3	30.389
137	1936.9	24.0	24.036	192	3441.1	30.4	30.499
138	1961.0	24.1	24.162	193	3471.6	30.6	30.609
139	1985.2	24.2	24.288	194	3502.3	30.7	30.719
140	2009.5	24.4	24.414	195	3533.1	30.8	30.829
141	2034.0	24.5	24.541	196	3563.9	30.9	30.938
142	2058.6	24.6	24.667	197	3594.9	31.0	31.047
143	2083.4	24.7	24.793	198	3626.0	31.1	31.156
144	2108.2	24.9	24.920	199	3657.3	31.2	31.265
145	2133.2	25.0	25.047	200	3688.6	31.3	31.373
146	2158.3	25.1	25.170	201	3720.0	31.4	31.481
147	2183.6	25.2	25.293	202	3751.5	31.5	31.589
148	2208.9	25.4	25.417	203	3783.2	31.6	31.697
149	2234.4	25.5	25.540	204	3814.9	31.8	31.805
150	2260.0	25.6	25.663	205	3846.8	31.9	31.912
151	2285.7	25.7	25.786	206	3878.8	32.0	32.019
152	2311.6	25.9	25.910	207	3910.8	32.1	32.126
153	2337.6	26.0	26.033	208	3943.0	32.2	32.233
154	2363.7	26.1	26.152	209	3975.3	32.3	32.339
155	2389.9	26.2	26.270	210	4007.7	32.4	32.445
156	2416.2	26.3	26.388	211	4040.2	32.5	32.551
157	2442.7	26.4	26.507	212	4072.8	32.6	32.657
158	2469.2	26.6	26.625	213	4105.5	32.7	32.763
159	2495.9	26.7	26.742	214	4138.3	32.8	32.868
160	2522.7	26.8	26.860	215	4171.2	32.9	32.973
161	2549.6	26.9	26.977	216	4204.3	33.0	33.078
162	2576.7	27.0	27.094	217	4237.4	33.1	33.183
163	2603.8	27.2	27.211	218	4270.6	33.2	33.287
164	2631.1	27.3	27.327	219	4304.0	33.3	33.391
165	2658.5	27.4	27.443	220	4337.4	33.4	33.495

Table 2 (continued)

T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)	T (°K)	E (μV)	ΔE (μV)	dE/dT ($\mu V/deg.K$)
221	4371.0	33.5	33.599	261	5795.4	37.5	37.565
222	4404.6	33.7	33.702	262	5833.0	37.6	37.659
223	4438.4	33.8	33.806	263	5870.7	37.7	37.753
224	4472.2	33.9	33.909	264	5908.5	37.8	37.847
225	4506.2	34.0	34.012	265	5946.4	37.9	37.941
226	4540.2	34.1	34.114	266	5984.4	38.0	38.035
227	4574.4	34.2	34.217	267	6022.5	38.1	38.128
228	4608.7	34.3	34.319	268	6060.7	38.2	38.222
229	4643.0	34.4	34.421	269	6098.9	38.3	38.315
230	4677.5	34.5	34.523	270	6137.3	38.4	38.407
231	4712.1	34.6	34.624	271	6175.8	38.5	38.500
232	4746.8	34.7	34.725	272	6214.3	38.5	38.592
233	4781.5	34.8	34.826	273	6252.9	38.6	38.684
234	4816.4	34.9	34.927	274	6291.7	38.7	38.776
235	4851.4	35.0	35.028	275	6330.5	38.8	38.868
236	4886.5	35.1	35.128	276	6369.4	38.9	38.959
237	4921.6	35.2	35.228	277	6408.4	39.0	39.050
238	4956.9	35.3	35.328	278	6447.5	39.1	39.141
239	4992.3	35.4	35.428	279	6486.7	39.2	39.232
240	5027.8	35.5	35.527	280	6526.0	39.3	39.322
241	5063.4	35.6	35.627	281	6565.3	39.4	39.413
242	5099.0	35.7	35.726	282	6604.8	39.5	39.503
243	5134.8	35.8	35.824	283	6644.3	39.5	39.592
244	5170.7	35.9	35.923	284	6684.0	39.6	39.682
245	5206.7	36.0	36.021	285	6723.7	39.7	39.771
246	5242.7	36.1	36.120	286	6763.5	39.8	39.861
247	5278.9	36.2	36.217	287	6803.4	39.9	39.949
248	5315.2	36.3	36.315	288	6843.4	40.0	40.038
249	5351.5	36.4	36.413	289	6883.5	40.1	40.127
250	5388.0	36.5	36.510	290	6923.7	40.2	40.215
251	5424.5	36.6	36.607	291	6963.9	40.3	40.303
252	5461.2	36.7	36.704	292	7004.3	40.3	40.391
253	5497.9	36.8	36.800	293	7044.7	40.4	40.478
254	5534.8	36.8	36.896	294	7085.2	40.5	40.566
255	5571.7	36.9	36.993	295	7125.8	40.6	40.653
256	5608.8	37.0	37.088	296	7166.5	40.7	40.740
257	5645.9	37.1	37.184	297	7207.3	40.8	40.826
258	5683.2	37.2	37.280	298	7248.2	40.9	40.913
259	5720.5	37.3	37.375	299	7289.2	41.0	40.999
260	5757.9	37.4	37.470	300	7330.2	41.0	41.085

The given composition (2.1 atomic per cent cobalt) is an unstable solution²¹ and the cobalt atoms will gradually diffuse to grain boundaries, with elevated temperatures accelerating the process.

As mentioned previously, in the section on apparatus the main errors of measurement are caused by the local inhomogeneities of the wires. Conversely, the deviations of the experimental calibration points for a given thermocouple from a smoothed curve should give an indication of the inhomogeneities of the wires. Typical deviation plots for gold-cobalt versus copper and constantan

versus copper are given in Figures 6 and 7, respectively. An earlier run on constantan (from another source) versus copper gave deviations as large as 6 μV between 20° and 80° K. The newer material is clearly much more homogeneous.

Additional tests for local inhomogeneities are made by dipping a loop of the particular thermocouple wire into a refrigerant while the ends are connected to a potentiometer. The galvanometer deflections indicate the potential differences between different sections of the wire subjected to the same temperature gradient. The

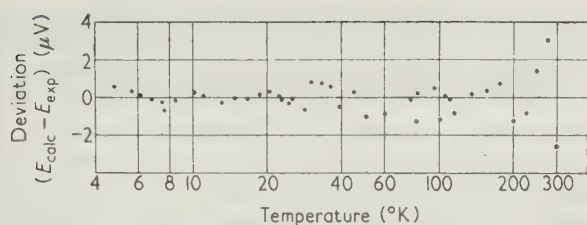


Figure 6. Typical deviations of experimental calibration points from a smoothed curve for a single gold-cobalt versus copper thermocouple

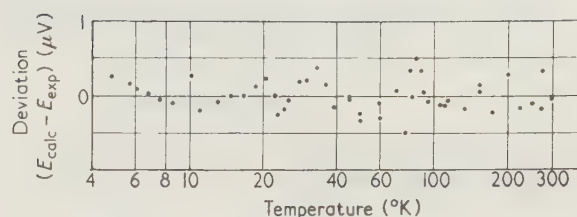


Figure 7. Typical deviations of experimental calibration points from a smoothed curve for a single constantan versus copper thermocouple

maximum and average inhomogeneity voltages for several copper, constantan, gold-cobalt, and 'normal' silver wires are given in Table 4. Indications of inhomogeneity obtained from dip tests are usually larger than those obtained in the calibration apparatus. This is caused by the much greater temperature gradients present in the dip tests.

Another test for homogeneity which is applicable to short samples (about 6 ft) arises as a by-product of a technique for making fixed point calibrations of thermocouples. It involves making up a symmetrical differential thermocouple of copper-test-wire-copper. The junctions are dipped into two baths of different temperatures, for example of melting ice or boiling cryogenic fluids. A change in the thermoelectric potential difference upon interchanging both the junctions in the baths and the junctions at the potentiometer terminals is an indication of inhomogeneity. Earlier lots of gold-cobalt gave differences on interchanging the junctions of about 30 μV between 4° and 76° K, and about 6 between 76° and 273° K. A recent lot, *Bar 9*, gave substantially lower differences, about 4 μV , at the higher temperatures. Constantan and 'normal' silver do not show variations greater than those given in Table 4. A test thermocouple system of instrument grade copper versus thermocouple grade copper gave total readings of about 4 μV between 4° and 76° K and about 3 μV between 76° and 300° K.

Summary and recommendations

Both gold-cobalt and constantan have a sufficiently large thermoelectric power against copper or 'normal' silver to allow their use in thermometry at temperatures down to 4° K. Gold-cobalt has a much larger sensitivity than constantan but this advantage is unfortunately offset by larger inhomogeneity voltages which therefore cause approximately the same relative error. For precise work two precautions are necessary to reduce the effects of inhomogeneities. First, a reference junction should be as close thermally to the variable junction as is possible. Second, alloy wires should not be taken through regions where the temperature is greatly different from either junction or where there are large temperature gradients. For example, it would be very poor practice to measure a temperature near 25° K using a reference junction at the ice point (273.15° K) if a bath at the hydrogen boiling

Table 3. Silver-0.37 Atomic Per Cent Gold versus Copper Thermocouples

T (°K)	E (μV)	dE/dT ($\mu\text{V}/\text{deg. K}$)
5	0.00	0.00
10	0.01	0.005
15	0.07	0.02
20	0.2	0.06
25	0.6	0.16
30	1.8	0.36
35	4.2	0.54
40	7.2	0.67
45	10.9	0.80
50	15.2	0.86
55	19.5	0.88
60	24.0	0.88
65	28.3	0.88
70	32.7	0.89
75	37.2	0.88
80	41.6	0.86
85	45.8	0.82
90	49.8	0.77
95	53.5	0.74
100	57.2	0.73
110	64.3	0.70
120	71.2	0.67
130	77.7	0.65
140	84.1	0.63
150	90.3	0.62
160	96.5	0.62
170	102.7	0.64
180	109.2	0.65
190	115.6	0.63
200	121.8	0.63
210	128.2	0.64
220	134.6	0.66
230	141.3	0.68
240	148.2	0.70
250	155.2	0.71
260	162.3	0.72
270	169.6	0.73
280	176.9	0.74
290	184.4	0.76
300	192.3	0.77

Table 4. Inhomogeneity of Thermoelectric Voltages
Obtained from Dip Tests

Samples†	Bath temperatures			
	4–300° K		76–300° K	
	Voltage (μV)		Voltage (μV)	
	Maximum	Average	Maximum	Average
(1) Cu	4.5	2.5	2.0	0.8
(2) Cu	1.8	0.7	1.0	0.3
(3) Constantan	0.5	0.2	0.5	0.2
(4) Au–Co	5.0	3.0	4.0	2.5
(5) Au–Co	5.5	3.5	4.0	2.5
(6) Ag–Au	2.2	1.2	1.2	0.8

† Samples were: (1) Instrument grade copper, 32 A.w.g.; (2) Thermocouple grade copper, 36 A.w.g.; (3) Thermocouple grade constantan, 36 A.w.g.; (4) Gold–cobalt, Bar 9, 36 A.w.g. (1960); (5) Gold–cobalt, Bar 5, 36 A.w.g. (1958); (6) 'Normal' silver, 36 A.w.g.

point (20.4° K) were available. It would also be undesirable to use a 20° K reference junction with interconnecting gold–cobalt or constantan wires leading out to room temperatures and then back to a 25° K region.

Because of variations between different lots or continuous composition gradients within a single lot, it is important to spot-calibrate each sample of gold–cobalt. This precaution is also necessary for constantan for work below 80° K. Above that temperature, constantan is much more reliable thermometrically. The regularity of the deviation curves in Figures 3 and 4 indicates that it is acceptable to construct a complete recalibration table for any new thermocouple by calibration at a few fixed points, followed by a linear interpolation of the deviations from the appropriate reference table. The main problem for low temperature thermocouple thermometry is at present one of chemical metallurgy. Advances in precision can be made only after substantial improvements are made in sample homogeneity. In general, constantan is strongly preferred for work above 80° K; gold–cobalt is slightly better for the lower temperatures.

Copper and 'normal' silver have approximately the same absolute thermoelectric power; both are useful in conjunction with gold–cobalt or constantan. Thermocouple grade copper is slightly more homogeneous than 'normal' silver. However, 'normal' silver has a lower thermal conductivity than copper, particularly at low temperatures, and therefore better insulates the actual thermocouple junction from heat sinks or sources along

the thermocouple lead wires. In general, copper is preferred above 80° K; 'normal' silver is preferable below 80° K where heat leaks along wires can be important.

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Measurement of Thermal Expansion at Low Temperatures

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AN important aim in solid state physics is the understanding of lattice dynamics, which may be revealed by measurements of such lattice properties as specific heat, elastic constants, and thermal expansion. Of these three properties the first two have been measured for a large number of elements in a suitably pure form and for some important binary alloys, over a wide range of temperatures including temperatures which are very low in relation to their Debye characteristic temperature θ_D . For maximum information to be obtained, the lower temperature limit must be in the vicinity of $\theta_D/100$, where the wavelengths of the thermal waves in a solid are long in comparison with the interatomic distance and hence where the solid may be regarded as the elastic continuum envisaged by Debye (for example, see review articles on heat capacity¹⁻³). Although data on specific heat and elastic constants have been obtained at such temperatures, complementary data on thermal expansion, which could tell us about the anharmonic nature of the interatomic forces,⁴ only extends down to temperatures near $\theta_D/10$.

In metals the free electrons may also contribute to the expansion⁵⁻⁷ as they do to the heat capacity. Theoretically we might expect the electronic contribution to the expansion coefficient to vary linearly with temperature, and therefore to become the major component at sufficiently low temperatures (say $T \lesssim \theta_D/50$), where the lattice component should vary as T^3 .

The approximate value of the thermal expansion coefficient which is to be detected at low temperatures may be estimated from Grüneisen's expression

$$3\alpha = \gamma C/KV \quad \dots (1)$$

where α is the linear expansion coefficient, γ the Grüneisen (or 'anharmonicity') parameter, C the specific heat, V atomic volume, and K the modulus of incompressibility. If $\gamma \simeq 2$, $V \simeq 10 \text{ cm}^3$, $K \simeq 10^{12} \text{ dyn/cm}^2$, and C is assumed to be given by the lattice component at low temperatures, namely $C \simeq 1946 \times 10^7 (T/\theta_D)^3 \text{ erg/g.-mol}$, then

$$\begin{aligned} \alpha &\simeq 1.3 \times 10^{-8} (T/\theta_D)^3 \\ &\simeq 10^{-8} \text{ per deg.K} \quad \text{for } T/\theta_D = 1/50 \end{aligned}$$

Hitherto most methods of measuring thermal expansion have been much too insensitive to detect length changes of the order of 10^{-8} cm . These include the interferometer,⁸ the X-ray diffractometer,⁹ and methods using a two-terminal capacitor.¹⁰

Recent developments in the precise measurement of small capacitances have made it possible to detect such changes. These are based on the comparison of three-terminal capacitors in a bridge circuit with transformer ratio arms, and are largely due to the efforts of A. M. Thompson and his group in the C.S.I.R.O. Division of Electrotechnology. Writing in 1958, Thompson¹¹ discusses 'the sensitivity that could be obtained with a capacitance probe for the measurement of mechanical displacement. The probe could take the form of a small disk with guard. . . . A disk diameter of 4 mm, spaced 0.1 mm from the reference surface, would give a direct capacitance of 1 pF. The gap would easily support 100 V giving a sensitivity of 10^{-7} pF . This corresponds to a change of only 10^{-8} mm in the separation of the surfaces. . . .'

Thompson's idea has been applied to the problem of determining linear expansion in solids in the way described in the succeeding sections.

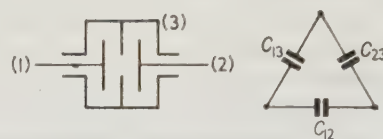


Figure 1. Three-terminal capacitor and its equivalent circuit

Measurement of small capacitances

In Figure 1 is sketched a three-terminal capacitor with its equivalent circuit. The conductor (3) completely surrounds the other two conductors and in practice forms the local earth shield; C_{12} is then the direct capacitance between (1) and (2) and is the only capacitance which is defined, that is, which does not involve the leads. Two such capacitors may then be connected in a transformer bridge (Figure 2) so that the ground capacitances C_{13} and C_{23} only shunt the ratio arms and the detector D . A small capacitance across the detector only reduces the sensitivity, and shunting the closely coupled ratio arms, which have a very small effective impedance, has negligible effect on the balance conditions (Figure 2)

$$\frac{C_A}{C_B} = \frac{V_B}{V_A}$$

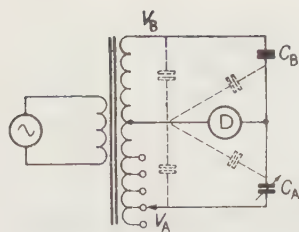


Figure 2. A transformer bridge for small capacitances, with a variable ratio or a variable capacitor

As discussed in detail by Thompson, the variable arm(s) of the bridge may be the transformer arm or the capacitance arm or both.

Figures 3 and 4 show the bridge used for the thermal expansion measurements. The bridge at present available has a detection limit of about 10^{-6} pF, which can be improved somewhat by using more elaborate detectors, e.g. a pre-amplifier and/or integrating detector, and by using higher voltage and higher frequency. The chief components are:

(1) Power amplifier, which boosts the available 1,000 c/s input to the 45 V required to supply the bridge.

(2) Ratio transformer, in which the tightly coupled sections of the secondary winding form two arms of the bridge. In most of the thermal expansion measurements to date the unknown C_X has been less than 10 pF (usually 4–5 pF) whereas C may be varied from 0 to 111·11110 pF in 10^{-5} pF steps; therefore the secondary winding has been tapped in the ratio 10:1 with 150 V applied to C_X and 15 V to the 'capacitance' C , then C_X can be read to 10^{-6} pF rather than to 10^{-5} .

(3) 'Capacitance' C (Figures 3 and 4), which is itself a bridge which has its range extended by being coupled to an available ratio transformer in such a way that a ten times larger voltage may be applied to the unknown capacitor C_X than is applied to C . It consists of a tapped inductance and seven fixed capacitors ranging through 100, 10, ..., 0·001, 0·0001 pF, each of which can be switched to any one of twelve tapings on the inductance, namely tapings from -1, 0, ... to +9, +10. The capacitors are of brass; the 100 and 10 pF units are made from concentric cylinders and the smaller ones from cylindrical plugs. Unfortunately their stability is affected both by temperature and humidity variations as they are unsealed. In

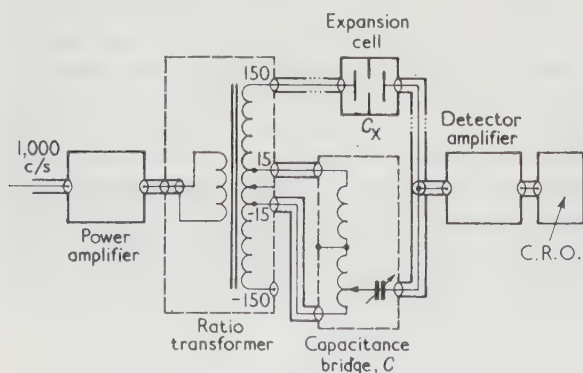


Figure 3. Block diagram of transformer bridge

initial experiments, drifts in the apparent value of C_X often corresponded to 20×10^{-6} pF in an hour due to these causes. This was much improved by thermally insulating the metal case of C in plastic foam and improving the temperature control of the room. Also, by connecting a sealed 50 pF capacitor (filled with dry nitrogen) in parallel with C , use of the 100 pF component could generally be avoided provided that C_X lay within the required limits, namely 5 to 6 pF or 50 to 60 pF. In future the author expects to eliminate these drifts almost entirely by replacing the

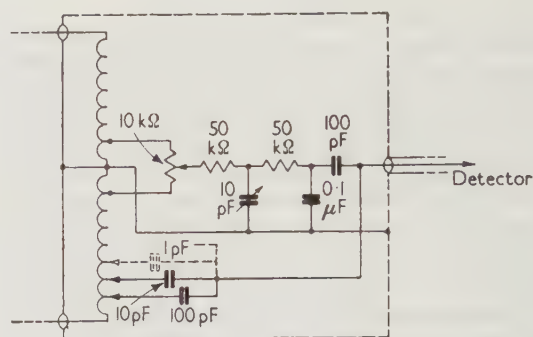


Figure 4. Details of conductance balance circuit and the 'variable capacitor' of Figure 3

variable C with sealed 1 and 10 pF capacitors, made from 'Invar' (the design of the 1 pF unit, due to M. C. McGregor, is shown in Figure 5). These will be switched across a six-dial ratio transformer (tapped auto-transformer commercially available from Gertsch Products, Inc., California) to give a bridge balance.

(4) Conductance balance, which is incorporated in the present bridge (see Figure 4 and discussion by Thompson¹¹ and by McGregor et al.¹²). A similar T-network will be used when the bridge is modified to use more stable capacitors and a Gertsch ratio arm. For this conductance balance, a phase angle correction of 10^{-4} radians or less is required so that the current from one capacitor to the detector will be identical in phase as well as magnitude with that from the other capacitor to the detector. The phase defect angle of the three-terminal capacitors may be small but it is not generally zero and seems to depend on the electrode surface layer.¹³ The small in-phase current required to be injected at the detector is provided by a T-network and a 10 kΩ wire-wound potentiometer which bridges two tapings of the inductance (Figure 4). The two 50 kΩ resistors are high stability carbons and the 100 pF and 0·1 μF capacitors are of silvered mica, while the 10 pF is a brass air condenser used to trim the phase angle initially to suit the bridge frequency.

(5) The detector, which is a tuned amplifier similar to that described by Johnson and Thompson.¹⁴ It is cathode-coupled with very low intermodulation, the output being displayed on an oscillograph.

(6) Stable capacitors which, in the bridge available at present, are not representative of the best types currently being used and developed by Thompson and his colleagues. These capacitors are both humidity and temperature sensitive to an undesirable degree, and no details of their construction will be given. Figure 5 illustrates a stable 1 pF capacitor of the type which will shortly replace those on the present bridge. Here, one electrode is a solid 'Invar' cylinder (1) which is supported by two polythene bushes in an 'Invar' guard-ring cylinder (2); both bushes fit tightly on to (1), and one is rather tight in (2), but the other is an easy sliding fit. (2) is supported in a similar fashion inside the 'Invar' cylinder (3) which forms the other electrode. The whole is supported in a rather strain-free fashion in a brass case which is filled with dry nitrogen. Note that 'Invar', an alloy of low expansivity, is used, and that the method of support ensures that any temperature-induced changes in dimensions impose a minimum of constraint, and hence of strain, on the electrodes. Further designs for stable capacitors have been given by McGregor et al.¹², and others are being tested at the present time.

Capacitor expansion cell

Figure 6 shows cell No. 1 (differential or relative expansion), mounted in a cryostat. The first model was constructed from 'Invar' (or 'Nilo 36'), an alloy of iron with 36 per cent nickel, but was found to be unsuitable for low temperature measurements, as discussed below. The later cell is entirely of high conductivity (h.c.) copper apart from brass screws, spring washers, and mica insulating washers.

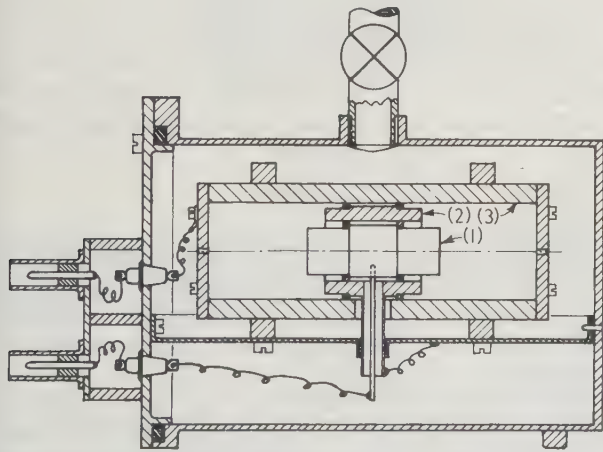


Figure 5. A 1 pF three-terminal reference capacitor, filled with dry nitrogen and kept at constant temperature. (After McGregor, private communication)

The copper parts have been machined to the required dimensions (or very slightly larger), stress-relieved by heat treating *in vacuo* at about 300°C for some hours, and final

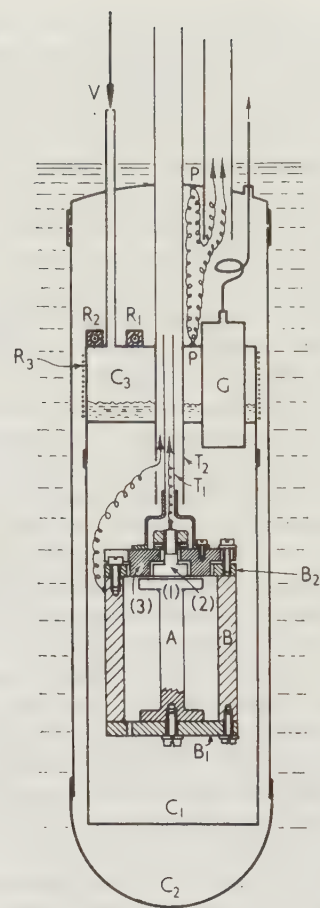


Figure 6. Differential expansion cell, mounted in a cryostat

machining performed. The central electrode (2), the guard ring (3), and the support ring B₂ have been assembled with insulating washers and brass screws into a unit whose lower face has then been ground and lapped, a tolerance of a few millionths of an inch being placed on the flatness. The cylinder B and end plate B₁ have similarly been ground and lapped. The overall length of B is 2.010 in. and the inner and outer diameters are, respectively, 1 ⁵/₁₆ in. and 1 ¹⁵/₁₆ in. Specimens (A) are machined and their end faces are ground and lapped to a length of 2.000 in., so that the gap between (1) and (2) which forms the capacitance C₁₂ (of Figure 1) is about 0.010 in. at room temperature. They are normally bobbin-shaped to reduce the mass of material to be cooled. The diameters of capacitance faces (1) and (2) are, respectively, ⁷/₈ in. (except for some samples which have been available only in slightly smaller diameter) and ¹/₂ in. The annular gap between electrodes (2) and (3) is 0.010 in. The lower lapped end of the specimen is held firmly on to the lapped surface of B₁ with a 4 B.A. screw and spring washer. To change samples, three screws which attach B₁ to the lower lapped surface of B are removed.

The electrical lead from electrode (2) is a 40 s.w.g. silk enamelled copper wire which goes up via a 3 mm diameter

german silver support tube T_1 to a B.P.O. connector (coaxial connector of the British Post Office pattern). A similar lead connected to B, and hence to electrode (1), goes up via the annular space between T_1 and the 10 mm diameter german silver pumping tube T_2 to another B.P.O. connector. Electrically these tubes are earthed, being connected to the guard ring (3) and to the surrounding metal cryostat. Otherwise the cryostat is rather conventional (White,¹⁵ page 158); the inner copper chamber C_1 is filled with about $\frac{1}{10}$ mm helium exchange gas to promote thermal equilibrium, and is attached by Woods metal to the chamber C_3 . This chamber, C_3 , is temperature controlled either (a) by pumping on liquid helium (1–4° K) or liquid oxygen (55–90° K) which has been drawn in through valve V, or (b) by electronically controlled heating. In this latter method, used between 4 and 50° K. and above 90° K, a 900 Ω resistance R_3 of manganin and copper (40 Ω copper bifilar wound with 860 Ω manganin) constitutes a thermometer which is one arm of an a.c. Wheatstone bridge. The signal from the bridge is amplified (Sommers¹⁶ or Wylie¹⁷), phase detected, and then fed back into a heater R_1 , a 200 Ω carbon resistor which is cemented into a copper sleeve on C_3 . For temperature measurement there are available (a) a helium-filled gas thermometer G, (b) a thermocouple of gold + 2.1 per cent (at) cobalt versus copper attached at points P, and (c) a 56 Ω Allen Bradley carbon resistance R_2 . The gold–cobalt alloy is glass-fibre insulated wire supplied by Sigmund Cohn Corporation (New York). Calibration data have kindly been provided by Dr. R. L. Powell, of the National Bureau of Standards; the thermocouple has been checked against the gas thermometer G to guard against any peculiarities in this particular alloy sample, including strains introduced during mounting.

The outer vacuum jacket C_2 is of brass and is easily removed by warming a Woods metal seal at the top end.

Figure 7 shows cell No. 2 (absolute expansion). In the previous cell (No. 1, Figure 6), the materials A and B both expand or contract with change in temperature; in fact, all the components change their temperature in the same way and therefore change their dimensions, so that the expansivity of A can be deduced only if that of B and the cell behaviour are known. By contrast, cell No. 2 (Figure 7) has been made in which absolute measurements are obtained directly; this was designed principally to give information on h.c. copper, and hence to determine the expansivity of B in cell No. 1.

The absolute cell was made from h.c. copper which was stress-relieved after initial machining. The definite capacitance C_{12} is formed by the annular gap of approximately 0.010 in. between the copper cylinder (1) (1.5 in. dia.) and an outer cylinder (2) of width $\frac{5}{8}$ in. and thickness $\frac{1}{8}$ in. The inner cylinder is centrally supported by a glass ball ($\frac{1}{8}$ in. diameter ground and polished to be not more than 6×10^{-6} in. out of round) at either end. It is quite free to expand radially and this expansion is measured by a change in C_{12} . Axially there is also a minimum constraint—provided the expansion is not more than a few thousandths of an

inch—because the small copper block B is soldered to the centre of a flexible diaphragm D which is secured only at its circumference.

The electrode (2) is separated from (3) and from the sleeve cylinder S by a thin layer of 'Araldite' cement, 0.010 in. thick. The sleeve S fits closely on to (3) and is soft soldered to it. The lead from (2) goes through a german silver shielding tube T_1 up to a B.P.O. connector at the top of the cryostat. Similarly another lead from (1) goes up the central pumping tube T_2 together with the two leads to the carbon heater R_1 (200 Ω) and two leads to a gold + 2.1 per cent (at.) cobalt versus copper thermocouple anchored at points P. The top plate C is attached to the flange of (3) with twelve 8 B.A. brass screws. A 0.005 in. thick polythene gasket provides a vacuum seal.

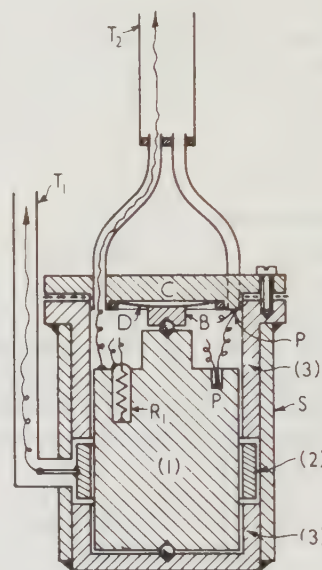


Figure 7. Absolute expansion cell, directly immersed in liquid refrigerant

As in the case of the differential cell all the electrical leads of 40 s.w.g. silk enamelled copper are thermally anchored at the temperature of the liquid bath by wrapping them around a small copper post and painting them with nail varnish.

In operation the cell is immersed in liquid helium or liquid oxygen with helium exchange gas initially around the inner cylinder (1). The exchange gas is then pumped away and the cylinder (1) may be heated to a required temperature by passing a current of up to 30 mA through the resistor R_1 . The temperature difference between (1) and the wall of C is recorded and the heater current adjusted manually to give a steady condition before measuring the capacitance.

The glass balls have proved a quite stable means of support, both mechanically and thermally. With the inner

cylinder at 29°K and surrounding liquid at 4.2°K, the cooling rate of the inner cylinder is 0.1 deg.K/min when the current through R_1 is reduced to zero. This corresponds to a heat loss of 0.022 W for a temperature difference of 25°K or an average thermal conductance of $0.022/25 \approx 1$ mW/deg.K for the two glass balls and their contact areas. With liquid oxygen ($T=90^\circ\text{K}$) surrounding the cell, and a temperature difference of 2°K, the cooling rate is 3×10^{-3} deg.K/min, corresponding to a heat loss of 0.0055 W for 2°K difference, i.e. a conductance of about 3 mW/deg.K. This relatively low heat transfer ensures that the inner conductor is in thermal equilibrium. Equally reassuring is the fact that the author has been able to carry out heat capacity measurements using the cell as a calorimeter, and to obtain values at 91°K and at 26°K which agree well with the published data.¹

Calculation of results

Cell No. 1 (differential). For an ideal parallel plate capacitor having plates each of area A cm² and separated l cm in a medium of dielectric constant ϵ ,

$$C = \epsilon A / 4\pi l \text{ e.s.u.} \quad \dots (2)$$

The gas medium in the expansion cell is helium at a pressure of less than 1 mm Hg. Even at atmospheric pressure helium has a dielectric constant very close to unity ($\epsilon = 1.00007$ at 0°C^{18}). Therefore we may assume $\epsilon = 1$, which is also true for cell No. 2 in which a high vacuum is maintained.

In any parallel plate capacitor, even with guard ring provided, there is a distortion of the electric field near the edge of the plate. Therefore a correction must be made to equation (2) which approximates to an increase in the effective area of the central electrode from A to $A + \Delta A$, where ΔA is the area of an additional strip extending over half the width of the gap, w cm, between the electrode and the guard ring. A formula due to Maxwell (discussed by Hartshorn¹⁹) gives

$$C = \frac{\pi r^2}{l} + \frac{\pi r w}{l + 0.22w} \left(1 + \frac{w}{2r}\right) \quad \dots (3)$$

where r is the radius of the central electrode (electrode (2), Figure 6). Note that the correction term for the guard-ring gap in this formula is

$$\frac{\Delta C}{C} = \frac{\Delta A}{A} \approx \frac{w}{r} \left(\frac{l}{l + 0.22w} \right) \quad \dots (4)$$

For the cell which is shown in Figure 6, $2r = 0.5$ in. = 1.27 cm, $w = 0.0254$ cm, and hence

$$C = \frac{0.112}{l} + \frac{0.004567}{l + 0.00559} \text{ pF} \quad (1 \text{ pF} = 0.9 \text{ e.s.u.}) \quad \dots (5)$$

From equation (5), for example, $l = 0.0200$ corresponds to $C = 5.778468$ pF and $\Delta C/\Delta l \approx 2.86 \times 10^{-6}$ pF per 10^{-8} cm.

Cell No. 2 (absolute). For coaxial cylinders of radii a_1 and a_2 ($a_1 < a_2$), the capacitance per unit length is

$$C = [2 \ln(a_2/a_1)]^{-1} \quad \dots (6)$$

If the shorter cylinder (electrode (2), Figure 7) is of length L and there is a gap of width w between itself and the guard ring, we correct equation (6) with a term given by equation (4), thus

$$C = L[2 \ln(a_2/a_1)]^{-1} \left[1 + \frac{wl}{L(l + 0.22w)} \right] \text{ e.s.u.} \quad \dots (7)$$

where $l = a_2 - a_1$.

For the cell described here, $w = 0.0254$ cm, $L \approx 1.5875$ cm, $a_2 \approx 1.8948$ cm, $a_1 \approx 1.8694$ cm. Substituting in equation (7) and expanding the logarithmic term for $l = a_2 - a_1 \ll a_2 + a_1$

$$C \approx \frac{1.649}{l} \left[1 + l \left(\frac{0.016}{1 + 0.00559} + 0.2675 \right) \right] \text{ pF} \quad \dots (8)$$

For $l \approx 0.0275$ cm this yields $C \approx 61.20203$ pF.

Formulae (6), (7), and (8) are correct only if the cylinders are truly coaxial. If their centres are not coaxial but are separated by a distance b , then²⁰

$$C = \left(2 \ln \frac{a_1^2 + a_2^2 - b^2 + 2bc}{2a_1 a_2} \right)^{-1} \text{ e.s.u.} \quad \dots (9)$$

where $(2bc)^2 = [(a_2 + a_1)^2 - b^2][(a_2 - a_1)^2 - b^2]$

$$\approx \left[2 \ln \frac{a_2}{a_1} \left(1 - \frac{b^2}{(a_2 + a_1)(a_2 - a_1)} \right) \right]^{-1} \text{ e.s.u.} \quad \dots (10)$$

for

$$a_2 + a_1 \gg a_2 - a_1$$

Substituting numerical values of a_2 , a_1 in equation (10), assuming $b \ll l \approx (a_2 - a_1)$, we may obtain, on expanding,

$$C \approx \frac{1.649}{l} \left[1 + 0.2675l + 0.5278 \left(\frac{b}{l} \right)^2 + \dots \right] \left[1 + 0 \left(\frac{w}{l} \right) \right] \text{ pF} \quad \dots (11)$$

Equation (11) indicates that C is rather insensitive to small eccentricities in the cell. Measurement of the dimensions after machining and of the capacitance confirm that equation (8) does not yield values seriously in error, and hence that b is sufficiently small (< 0.002 cm) compared with $l \approx 0.027$ cm. This cell is required to measure l with an error of less than 0.5 per cent and to measure very small changes in l with temperature, rather than to provide very precise true values of l . A rather comprehensive theoretical treatment of the effect of displacing the respective cylinder axes, of tilting them, and of offsetting the guard-ring was published in 1907 by Rosa and Dorsey.²¹

Accuracy of measurements

To obtain accurate values of the change in length of a sample as a function of a temperature (or perhaps as a function of some other physical parameter such as magnetic field), maximum sensitivity is needed in detecting changes in gap l rather than in determining true values for the gap l . A major limit in determining true values is set by a knowledge of constants in equations (5) and (8). The

dimensions of the electrodes and guard-ring gap w are uncertain to the extent of at least 0.001 cm, so that the constants 0.112 in equation (5) and 1.649 in equation (8) are uncertain to at least 2 parts in a thousand. However, provided any variation in these dimensions is insignificant as compared with variations in gap l , the requirements will be satisfied.

The principal random errors that affect the results arise from the following causes.

(1) Bridge sensitivity. Under this heading the author includes (a) the limited sensitivity of the detector, and (b) the stability of the reference capacitor. Thompson¹¹ and coworkers have achieved a detection limit of less than 10^{-7} pF, with a potential difference of the order of 100 V. The author's present limit of 10^{-6} pF with a similar voltage will doubtless be improved by a factor of 4–10 by using a new amplifier incorporating pre-amplifier, and by displaying the amplifier output on a more sensitive oscillograph or on an integrating detector, but might still be limited in practice by vibration upsetting the expansion cell. At present it appears that bridge sensitivity and temperature-induced drifts in the reference capacitor(s) impose the limit of 10^{-6} pF (corresponding to about 0.5×10^{-8} cm uncertainty in l). In the case of the absolute cell, the detection limit also corresponds to about 0.5×10^{-8} cm, but is only 10^{-5} pF in terms of capacity; the capacity is 10 times larger (60 pF compared with 5 pF for cell No. 1), so that only 15 V (rather than 150 V) are applied to the electrodes of the cell in order to stay within the range of the bridge.

(2) Instability in expansion cells. By virtue of their method of construction, these are sensitive both to mechanical shock and to thermal cycling, but not so as to affect their usefulness seriously with the present accuracy. Tests on both the copper cells at 293, 273, 90, and 4.2° K seem to show that they are quite stable in time. Drifts of the order of 1 part in 10^6 in capacitance (corresponding to 2×10^{-8} cm change in gap) which may occur over a period of 30 to 40 min can generally be traced to temperature drifts affecting the bridge. For some days, cell No. 1 was kept at 90° K, and the random drift in the reading of C , which amounts to a few parts in a million, could be correlated with this drift in the temperature of the reference capacitors.

Mechanically, cryostats are mounted on a frame of steel piping and are not well insulated from building vibrations. However, little effect is observed from these, but any sudden severe shock—banging the frame with the fist—alters the capacity reading discontinuously by 20 or even 50 parts in a million.

Thermal cycling over quite wide ranges of temperature produces little permanent effect in the absolute cell No. 2, but in cell No. 1 cycling from 90 to 4 to 90° K or from 293 to 90 to 293° K produces marked hysteresis, amounting to capacitance changes of 1 in 10^4 or even 1 in 10^3 ; this latter corresponds to about 3×10^{-5} cm change in gap. However, more restricted cycling, limited to the region from 4 to 30° K, produces no measurable effect. During a normal

series of observations in the range 4 to 30° K, the cell is cooled quite frequently (every 20–30 min) back to 4.2° K, in order to observe any slow drifts in C (4.2° K) which may arise from the drifts in room and bridge temperatures. No changes occur which may be traced to mechanical hysteresis effects.

An earlier 'differential' cell exactly similar in design to that of Figure 6 was made of 'Invar', in the hope that, in the temperature region of interest, below 30° K, its expansion coefficient would be very small in comparison with most samples being tested, and hence the cell itself would be almost constant in dimensions, only length of sample A changing. This alloy has a low expansion coefficient at room temperature, being about 1×10^{-6} deg. C⁻¹. Measurements of Beenakker and Swenson²² on the total thermal contraction of some technical materials below room temperature seemed to indicate that for 'Invar' there was no further measurable change in length (within their limits of $\pm 3 \times 10^{-5}$ in $\Delta L/L$) below 75° K, as would be expected if α behaved as it should for a normal crystalline solid, varying approximately as the Debye specific heat function. However, this was not to be, as the cell proved to have a negative expansion coefficient below 40 or 50° K. For example, below 20° K, measurements on beryllium relative to 'Invar' indicated that α ('Invar') $\simeq -9 \times 10^{-8} T$, thus being much too great at the lowest temperatures in comparison with most substances which we are concerned with testing. Another somewhat undesirable feature of 'Invar' for measurements of very high sensitivity is the instability of the alloy itself, which causes its dimensions to change slowly over long periods of time; this latter effect can be reduced by suitable thermal ageing.²³ For room temperature measurements, such as those on chromium (illustrated in Figure 8), the 'Invar' cell has proved useful.

Another differential cell has been made in which the design and operation are similar to Figure 6, but the top section comprising electrode (2), guard ring (3), and

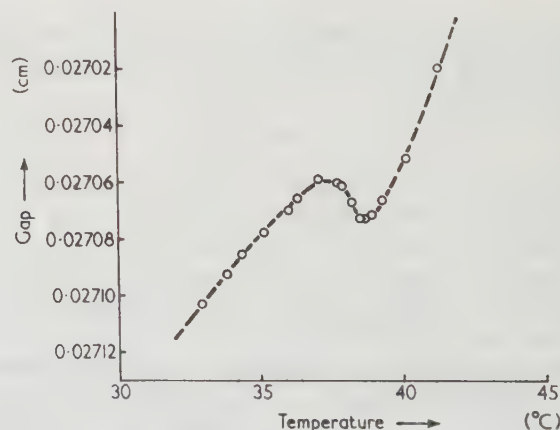


Figure 8. Change with temperature of gap between high purity chromium sample and 'Invar' cell ('differential')

ring B₂ are all cemented together with hot-setting 'Araldite' and then ground and lapped. Initial tests show that this may be more stable thermally and mechanically than the present design at room temperature, but is sensitive to mechanical vibrations at liquid helium temperatures.

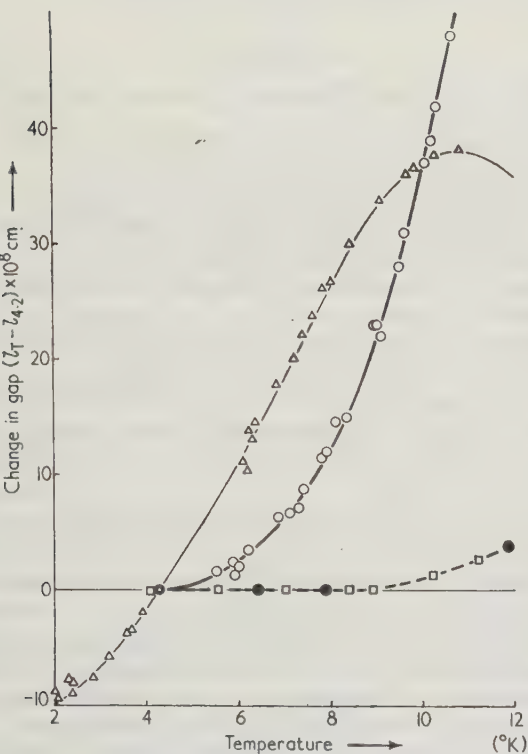


Figure 9. Change with temperature of the gap between copper cell (differential) and samples of high-conductivity copper (●), 99.999% 'ASARCO' copper (□), beryllium (○), 99.96% iron (△)

Experimental results

The most decisive test of this method of measuring expansion lies in the accuracy and reproducibility of experimental results obtained. In the accompanying Figures 8, 9, and 10 are plotted values of the capacitance gap, l , or the change in gap as a function of temperature. Figure 8 illustrates the change in length of a rod of ductile high-purity chromium relative to an 'Invar' frame (or cell) near room temperature. Figure 9 shows results obtained in cell No. 1 at low temperatures with samples of copper, iron, and beryllium. The experimental points for each sample were taken on more than one experimental run, and during each run frequent thermal cycling occurred back to 4.2° K as reference temperature. Initially, until the 'absolute' cell No. 2 was made, the results obtained with beryllium in the copper cell (No. 1) served as the best source of information on copper itself, because of the very small expansivity of beryllium at low temperatures. For beryllium the characteristic temperature θ_D is over 1,000° K as compared with about 300° K for copper, so that if the ratio α/C remains

similar at low temperatures to that found at normal temperatures, then $\alpha(\text{Be})$ should be only a small fraction (about 3 per cent) of $\alpha(\text{Cu})$. In Table 1 are results for

Table 1. Comparison of Expansivity Data for Copper Obtained in Cells No. 1 and No. 2. Values are Tabulated of the Total Change in Gap and of the Change in Gap per Centimetre, all expressed in 10^{-8} cm units

	4.2° K	10° K	15° K	20° K
Be in Cu, cell No. 1	0	38	220	753
Cu in Cu, cell No. 1	0	1	14	61
Thus Cu relative to Be	0	37	206	692
Be expansion (calc.)	0	4	11	26
Thus Cu expansion	0	41	217	718
Thus Cu expansivity (per cm)	0	8.1	42.7	141.3
Cf. Cu in cell No. 2 (per cm)	0	8.3	42.8	140.1

beryllium in copper, together with corrections for (1) cell behaviour as revealed by measurements of copper in copper, and (2) above-mentioned beryllium expansion as calculated from specific heat data (obtained from 4 to 300° K by Hill and Smith²⁴) and expansion data obtained above 100° K.^{25, 26} These may be compared with results obtained on h.c. copper directly in cell No. 2 (Figure 10) after dividing by the appropriate sample dimension, that is, dividing by axial length of 5.08 cm for sample in cell No. 1, by radius 1.87 cm for sample in cell No. 2. The agreement is quite good.

The remarkable change in gap shown by the iron specimen below 4° K (Figure 9) is taken as evidence of an

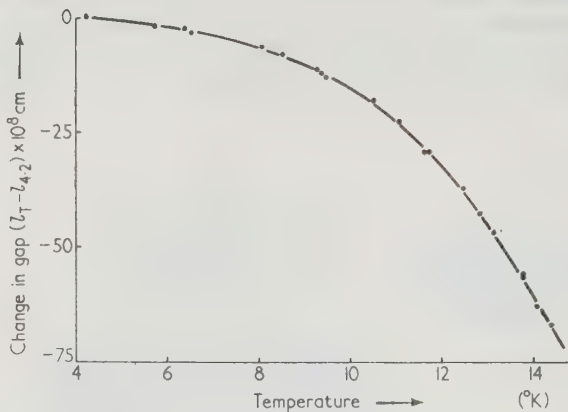


Figure 10. Change in gap between copper cylinder (temperature varying) and 'absolute' copper cell No. 2 (temperature fixed at 4.23° K)

electronic contribution to thermal expansion. Detailed discussions of the evaluation of the expansion coefficient α , and the physical significance of our results on copper, iron, aluminium, and chromium will be published elsewhere. A preliminary note concerning copper and iron has already appeared.^{27, 28}

Discussion and conclusions

It seems clearly established that modern techniques for comparing small capacitances of the three-terminal type can be applied to determining linear expansion with a detection sensitivity and reproducibility of 10^{-8} cm or less. With the aid of improved amplifier-detectors, more stable reference capacitors, and smaller gaps and higher voltage, this limit may easily reach 10^{-9} cm. Perhaps an increase in frequency from 1 kc/s to 10 kc/s may help.

In order to take full advantage of this lower limit, modifications in the expansion cell may be needed to give the appropriate mechanical stability. In this connection, the type of ball-mounting used in cell No. 2 seems preferable to the lapped surfaces in cell No. 1, but difficulties in preparing and mounting specimens of certain shapes or sizes have also to be taken into account. Also the magnitude of the capacitance to be measured needs to be within particular limits if an available bridge is to be used, i.e. a bridge incorporating available reference capacitors and transformer ratios. The present cells certainly seem adequate for giving very useful information about thermal expansion in such solids as the superconductors lead and niobium, the transition elements palladium and chromium, the monovalent elements copper and silver, and some alkali halides which we are planning to study down to temperatures below $\theta_D/50$. Whether they will yield sufficiently accurate information about the electronic expansion term in the non-transition metals is doubtful, so that we are considering improvements in design.

It is a pleasure to express our indebtedness and thanks to Mr. A. M. Thompson and Mr. M. C. McGregor, of the C.S.I.R.O. Division of Electrotechnology, who have been most generous with their advice, assistance, and equipment.

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The Application of Superconductivity to the Detection of Radiant Energy

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THE most sensitive detectors of radiant energy operating at room temperature have reached that stage of refinement when the limit of detectivity is set by fundamental sources of noise. The best thermal detectors (bolometers, thermocouples, pneumatic cells) and photodetectors (photoconductive and photoelectric cells) are both within an order of magnitude of the ultimate sensitivity set by the fluctuations in the exchange of radiated energy with the surroundings. A major improvement in detectivity can be obtained only by having recourse to lower temperatures of operation.

It is generally extremely difficult, however, to take advantage of a low operating temperature with a thermal detector. This is because thermoelectric powers and temperature coefficients of resistance normally decrease with decreasing temperature. Superconducting metals provide notable exceptions to this rule. On cooling through its transition temperature, T_c , a sample of a superconducting metal loses its resistance entirely over a temperature interval which can be as small as 0.001°K . Andrews¹ suggested many years ago that the remarkably high temperature coefficient of resistance of a superconductor close to T_c made it particularly suitable for use as a bolometer element, and since then a number of superconducting bolometers have been constructed and tested.²⁻⁴ Noise in the contacts with the elements or difficulties of operation were met, however, and none of these bolometers has been used in spectrometry. In this paper, we describe the superconducting bolometers which we have recently developed and the mode of operation which has made possible their use in spectrometry with a very considerable gain in sensitivity over conventional detectors.

Improved detectors are particularly required for spectrometry in the extreme infra-red, at wavelengths between 0.1 and 1.0 mm. On each side of this spectral range—in the near infra-red and in the microwave regions—resolutions of 1 part in 10^6 are attainable. In the extreme infra-red the best resolution obtained with room temperature detectors is about 1 part in 10^2 . Our bolometers are being used for spectrometry in the extreme infra-red,⁵ and the cryostats used for this purpose will be described.

The bolometer

The main features of one of our bolometers are illustrated in Figure 1. The sensitive element E is an evaporated

film of tin deposited on a mica substrate about $3\text{ mm} \times 2\text{ mm}$ in area and $3\text{ }\mu$ thick. This substrate is supported from a divided brass cylinder C by nylon threads $10\text{ }\mu$ in diameter and about 0.5 mm long. Electrical contact to the element is made through evaporated films of lead deposited on the nylon threads, ends of the mica strip, and faces of the divided cylinder. When the tin element is maintained at its transition temperature (about 3.7°K) the lead is well below its own superconducting transition (7.3°K) and provides perfect metallic electrical contact, in spite of its being sufficiently thin to maintain the thermal isolation necessary for a high responsivity to incident radiation. In use the space surrounding the bolometer is evacuated.

It is clear that a high degree of temperature stability is necessary. The vapour pressure in the helium reservoir to which the bolometer base is attached is controlled by a simple manostat which can maintain the temperature constant to within 10^{-3}°K indefinitely and which, by adjustment of the volume of a vessel containing gas at the reference pressure, enables the bolometer to be brought rapidly to any suitable point on its superconducting transition. A very fine control of temperature is then obtained by using the bolometer element itself as a sensing device to provide thermostatic control of the current passing through a heater H wound on the thermal sink. A nylon washer W separates the sink from the helium reservoir, so that it has a thermal time constant of a few seconds. This allows the temperature of the sink to vary under the control of the heater, so that the element remains

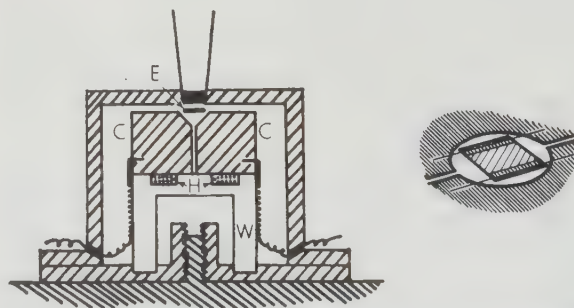


Figure 1. Constructional features of bolometer and its housing with details of the sensitive element

at a constant operating temperature within 10^{-5}°K in the face of the marked variation of the power incident upon the bolometer as the spectrometer turns through a spectrum. (The incident radiation is interrupted by a mechanical shutter at 10 c/s and the automatic control is damped so that it does not reduce the *alternating* response to the radiation.) The nylon washer also serves to reduce the influence of rapid fluctuations of temperature in the helium reservoir.

The electrical circuits

The amplification and control circuits used with the bolometer are illustrated in Figure 2. The bolometer B

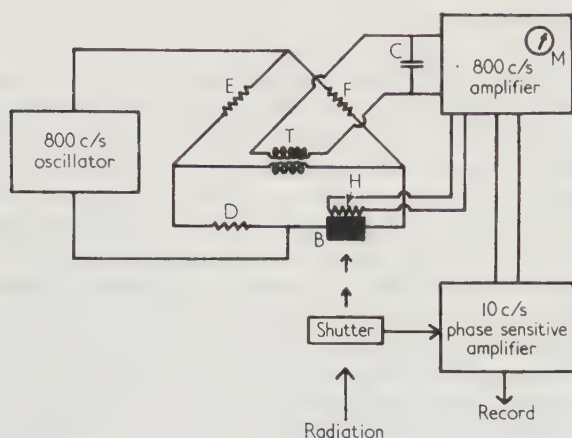


Figure 2. The circuits for amplification and control

forms one arm of a Wheatstone net. It has a resistance of about $10\ \Omega$. A constantan resistor D of approximately the same resistance forms the second arm, and is also at 3.7°K . The other arms E and F, outside the cryostat, are several kilohms, and can be varied to obtain the balance of the bridge. The off-balance current is amplified by a small transformer T operating in the helium reservoir. Its core is strip-wound with $50\ \mu$ thick mu-metal alloy of a special composition having an initial susceptibility of about 7,000 at 4°K , which was kindly prepared by the staff at the Post Office Research Station, London. The secondary is tuned to 800 c/s by the capacitor C.

The bridge is supplied with current alternating at 800 c/s. The radiation incident upon the bolometer is interrupted at 10 c/s by a rotating shutter in the spectrometer, and so the signal amplified by the transformer is amplitude-modulated at 10 c/s.

The output from the cold transformer is applied to an amplifier tuned to 800 c/s, which registers the mean carrier amplitude on an output meter M. The 10 c/s envelope is detected and, after further amplification, is rectified *in phase* with a square wave reference signal derived from the shutter unit. The output is smoothed by a circuit having a time constant which can be varied over the range from 1 to 40 sec, and is finally recorded on a strip-chart.

We find that the use of an alternating source of e.m.f. for the bridge, rather than a d.c. source, has a number of important advantages. First, the main amplification takes place at the carrier frequency and not at 10 c/s. It is then possible to obtain a larger useful turns-ratio with the transformer, and the vacuum-valve amplifier is quieter at the higher frequency. Second, the mean amplitude of the carrier signal from the bridge as displayed by the output meter M provides a direct and continuous indication of the resistance of the bolometer. Last, the mean amplitude of the carrier signal is used to control the current passed through the heater H on the bolometer sink, providing the thermostatic control described above.

The cryostat

The bolometer has been designed for use with a spectrometer which operates at wavelengths between 0.1 and $1.0\ \text{mm}$.⁵ The energy from the best sources of radiation at these wavelengths is extremely low, and such a spectrometer must have a large numerical aperture, in our case $f/2.2$. The main features of the cryostat which allow the bolometer to receive energy from a large solid angle are illustrated in Figure 3(a) and (b).

The single vacuum window W is at room temperature and is close to the exit slit of the spectrometer. Windows of quartz or of polyethylene are used, 1 mm or $\frac{1}{2}$ mm thick and 1 in. in diameter, with O-ring seals.

We have found a conical light-pipe to be more convenient than an external mirror for condensing the incident radiation on the bolometer. The cone CCC is 1.5 cm in diameter at the window and tapers to 3 mm at the

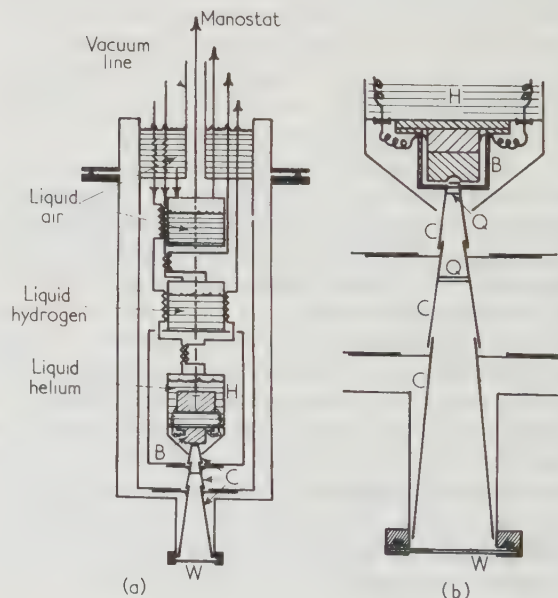


Figure 3. (a) Conical light-tube in cryostat, which condenses radiation on the bolometer; (b) The liquefier-cryostat, showing the nitrogen, hydrogen, and helium reservoirs, and conical light-tube

bolometer, and is 10 cm in length. The equivalent aperture of a conical light-tube can be calculated,⁶ and the one we use would be equivalent to a mirror of aperture $f/2.5$ if it were perfectly reflecting. There is a loss at the walls of the copper cone but this is probably less than would occur with a mirror because of the difficulty which would be encountered in maintaining a correctly focused image on the bolometer. The cone is made up of three parts which overlap slightly but which do not come into contact. The three segments are cooled to the temperatures of liquid air, liquid hydrogen, and liquid helium, respectively, being parts of the radiation shields attached to the reservoirs containing these refrigerants.

It is essential to prevent most of the radiation which is emitted by the warmer stages, particularly the room temperature apparatus, from reaching the bolometer. A power of 10^{-6} W is sufficient to raise the temperature of the element 4° K above that of the sink and this would make it impossible to reduce the element to its transition temperature at 3.7° K. Crystalline quartz radiation shields QQ are introduced in the cone segments attached to the hydrogen and helium reservoirs. These are opaque between 4 and $40\ \mu$. An additional 4° K filter is required, the material being selected for the particular part of the spectrum under study.

The bolometer is housed in a small box B attached to the base of the helium reservoir H. The transformer T is mounted in the reservoir H and the whole of the helium stage is wrapped with lead foil to provide a superconducting screen for that part of the system where the signal is at its lowest level.

The cryostat, drawn in full in Figure 3(b), serves also as a liquefier for hydrogen and for helium—though of course this is not an essential feature. It is of the type described by Jones,⁸ and can produce liquid helium by Joule-Kelvin expansion 90 min after the mounting of a bolometer. The capacity of the helium reservoir is $60\ \text{cm}^3$ which is sufficient for more than 2 hr use of the bolometer. The helium can is easily refilled.

The performance of the bolometer

The bolometer functions satisfactorily in conjunction with an extreme infra-red spectrometer.⁵ For example, it has been possible to record the pure rotation spectrum of weakly absorbing nitrous oxide from 0.6 to 0.8 mm wavelength, that is from $17\ \text{cm}^{-1}$ to $12.5\ \text{cm}^{-1}$, clearly resolving the lines which are separated by $0.8\ \text{cm}^{-1}$. Whereas previously the resolution attainable in this spectral region using grating spectrometers has been energy limited, the detectivity of the superconducting bolometer is such that the limit is now set by the quality of the gratings so far constructed. With the bolometer, a resolution better than $0.1\ \text{cm}^{-1}$ would be possible throughout the extreme infra-red, if suitable gratings were available. A perfect echelette grating 6 in. square and with a 15 degree groove angle has a theoretical resolution of about $0.10\ \text{cm}^{-1}$, and a close study of the quality of the gratings which we have made for

this region suggests that the attainable resolution is grating limited to about $0.3\ \text{cm}^{-1}$.

An absolute measurement of the minimum detectable signal of a bolometer can be made in the near infra-red. We have done this⁵ by comparing the signal-to-noise ratio of a superconducting bolometer with that of a Golay pneumatic detector which had been calibrated using a black-body source. The ratio for the bolometer was more than forty times greater than that of the Golay cell under identical optical conditions indicating a minimum detectable signal (for which the signal-to-noise ratio is unity)

$$W_m = 10^{-12}\ \text{W}$$

with a receiving area $3\ \text{mm} \times 2\ \text{mm}$ and an overall time constant for the system equal to 1.25 sec.

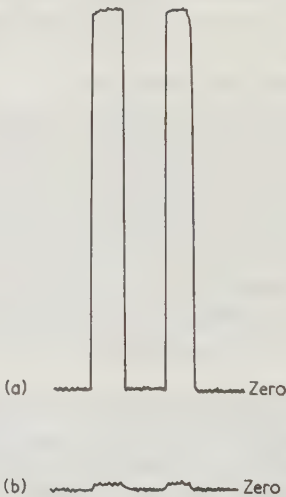


Figure 4. Pen-recorder traces showing the response to radiation at a wavelength of 1 mm of (a) a superconducting bolometer and (b) a Golay detector, under identical conditions

Figure 4 shows the response of a superconducting bolometer to the energy emerging from the spectrometer set at a wavelength of 1 mm, and also the response of the Golay cell under identical conditions. There is a difference of about $\times 100$ between the signal-to-noise ratios of the two detectors, a similar comparison to that found in the near infra-red. An absolute calibration in the extreme infra-red is impracticable, and an indirect argument is necessary to establish that the detectivity of the detectors is approximately uniform throughout the infra-red. Several absorbing films of the kind used in Golay detectors were kindly provided by Unicam Instruments Ltd. The transmissivity of these films decreased only slightly over the range from $2\ \mu$ to $500\ \mu$. We conclude that selected Golay detectors, and by implication superconducting bolometers, have

approximately constant sensitivities throughout the infrared, and that the minimum detectable signal for a superconducting bolometer of the kind described here is appreciably less than 10^{-12} W for a time constant of 1.25 sec. It is important to note that this figure is the *incident* power. The absorbing surfaces of the bolometers so far used have been the untreated surfaces of the tin films, and presumably only a small fraction of the incident power is absorbed. An improved performance would be obtained if a more absorbing surface could be formed.

Measurement and adjustment of bolometer constants

The characteristic constants of a bolometer are four: the resistance R of the element, the rate of change of resistance with temperature dR/dT , the thermal time constant of the element τ , and the thermal conductance G linking the element to the sink, which in our bolometers is mainly through the nylon leads with their coatings of lead. The thermal capacity of the element is equal to τG . It is necessary to have methods of measuring these constants for any bolometer, and we have found the following three simple experiments the most direct.

For R and dR/dT a transition curve is obtained by measuring R , with the bridge which incorporates the bolometer, as the bolometer is taken slowly through its transition, using the manostat control. An example is given in Figure 5, where it can be seen that dR/dT lies in the range from 100 to 1,000 $\Omega \text{ deg. K}^{-1}$. This is several orders of magnitude greater than that of normal metals at room temperature, and accounts for the large responsivity which enables us to gain advantage from the low temperature of operation.

The time constant τ is measured by recording the amplitude of the response of the bolometer to incident energy interrupted at various frequencies. Typical relaxation curves are shown in Figure 6, and the value of τ is given

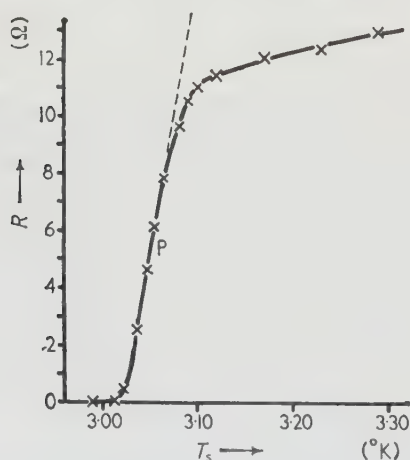


Figure 5. The transition to superconductivity of the sensitive element of a bolometer. At P, $dR/dT = 190 \Omega \text{ deg. K}^{-1}$

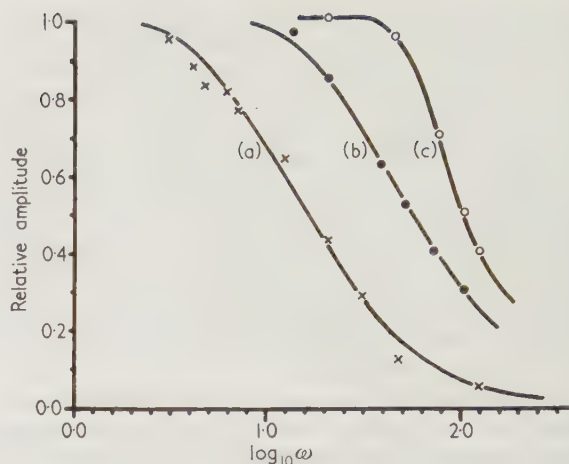


Figure 6. The amplitudes of the responses of three bolometers to incident signals interrupted at various frequencies ω : Curves (a) and (b) are for sinusoidal interruption and indicate bolometer time-constants of 110 msec and 30 msec, respectively; Curve (c) is for square-wave chopping and indicates a time-constant of 15 msec

by $\omega_c \tau = \sqrt{3}$, where ω_c is the frequency at which the response falls to half of its low frequency value.

To determine G the resistance of the element is measured for various values of the current i flowing through it, the sink temperature being maintained constant. At equilibrium

$$i^2 R = G(T - T_s)$$

where T is the temperature of the element and T_s that of the sink. Thus

$$\frac{d(i^2 R)}{dR} = G \frac{dR}{dT}$$

and G can be found from the slope of a graph of $i^2 R$ versus R , like that in Figure 7.

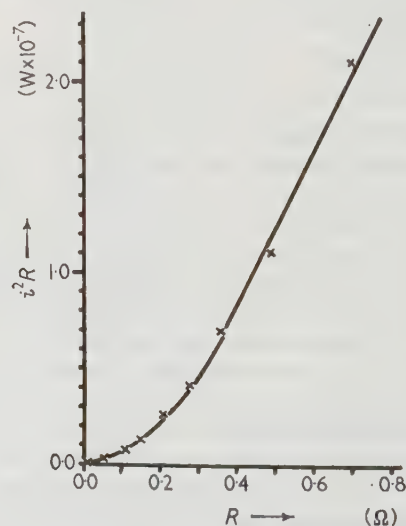


Figure 7. The dependence of the resistance of a bolometer on the Joule heat generated in it

The bolometer constants may be adjusted during construction. R and dR/dT depend on the thickness of the tin film. Very thin films deteriorate and, in any case, it will be seen that there is little to be gained by increasing R indefinitely. We generally have R between 1 and $10\ \Omega$ and dR/dT in the range 100 to $1,000\ \Omega\ \text{deg.K}^{-1}$. The thermal capacity of the element is kept low by the use of mica sheet cleaved to about $3\ \mu$ thickness. Thinner substrates, e.g. collodion, would be possible but the mica bolometers withstand repeated cooling to 4°K very satisfactorily. τ is adjusted, by a proper choice of G , to its optimum value, which we shall see is about 10 msec. For this, G must be about $3 \times 10^{-7}\ \text{W deg.K}^{-1}$ and such a value is obtained by an appropriate adjustment of the length of the nylon supports, care being taken to obtain a uniform and constant thickness of lead for this contributes significantly to the conductance to the sink.

Responsivity of superconducting bolometer

The properties of a bolometer are determined by the measurable constants τ , G , R , and dR/dT , and by the absorptivity a of the receiver surface. If a current of r.m.s. value i is passing through a bolometer when an interrupted incident signal power $W = W_0[1 - \exp(j\omega t)]$ is incident upon it, the heat balance equation for the element is

$$C \frac{dT}{dt} = i^2 R + W_0[1 - \exp(j\omega t)] - G(T - T_s)$$

where C is the thermal capacity of the element which is equal to τG . The alternating part of the solution to this equation is

$$T = T_0 \exp(j\omega t + \alpha)$$

where the amplitude T_0 is

$$T_0 = aW_0/G[\omega^2 \tau^2 + (1-b)^2]^{1/2}$$

where $\sqrt{b}$ is the ratio of i to that critical value of current for which the bolometer would be just unstable through Joule heating, i.e.

$$b = \frac{i^2}{i_c^2} = i^2 / G \frac{dT}{dR}$$

We assume that dR/dT is constant over the range of temperature T_0 .

The responsivity r of a detector is defined as the r.m.s. value of the alternating potential difference across the detector divided by the incident signal power $2W_0$. From the expression for T_0 , we thus obtain

$$\begin{aligned} r &= \frac{1}{\sqrt{2}} i T_0 \frac{dR}{dT} / 2W_0 \\ r &= \frac{1}{2\sqrt{2}} \frac{a(dR/dT)i}{G[\omega^2 \tau^2 + (1-b)^2]^{1/2}} \\ &= \frac{1}{2\sqrt{2}} \frac{a[bG(dR/dT)]^{1/2}}{G[\omega^2 \tau^2 + (1-b)^2]^{1/2}} \end{aligned}$$

It is clear that τ may be adjusted, by changing G , to an optimum value τ_r for maximum responsivity

$$\omega \tau_r = (1-b)$$

In practice the current is kept well below the critical value in order that the bolometer should not become unstable when tracing out a spectrum, and so $\omega \tau_r \simeq \frac{1}{2}$. Since ω is $2\pi \times 10\ \text{sec}^{-1}$ (a minimum practicable value set by the difficulties of amplification at low frequencies) the optimum value of τ is

$$\tau_r \simeq 10\ \text{msec}$$

Substituting typical measured values in the equation above gives

$$r \simeq 3 \times 10^2\ \text{V W}^{-1}$$

a value several orders of magnitude greater than the responsivity of ordinary thermocouples and bolometers. We used $a=0.1$ for the absorptivity of the receiving surface.

However, the detectivity of a detector is not determined by the responsivity alone. The noise which it generates must also be considered.

Noise from a superconducting bolometer

There are at least two fundamental sources of noise in a bolometer. These are the Johnson noise associated with its resistance and the temperature variations due to the fluctuations in the exchange of radiant or conducted heat with the surroundings.

The Johnson noise has a mean square potential given by

$$\overline{V_J^2} = 4kTRB$$

where k is Boltzmann's constant and B is the bandwidth of the detecting system. This potential is equivalent to an incident radiation signal power W_J , where

$$\overline{W_J^2} = \overline{V_J^2}/r^2$$

The noise due to fluctuating temperature has been discussed by Milatz and van der Velden.⁷ If the bolometer element were in thermal equilibrium with the sink the mean square fluctuation of temperature $\overline{\theta^2}$ would be determined by the thermal capacity τG , thus

$$\tau G \overline{\theta^2} = kT^2$$

The same order of magnitude would be expected even when there is a small temperature difference $(T - T_s)$ and we then obtain for the equivalent incident power

$$\overline{W_T^2} = \frac{1}{a^2} [4kT^2 G(1-b)B]$$

The mean square values for these separate sources will combine arithmetically, and we obtain for the incident signal equivalent to the two sources of noise

$$\overline{W_N^2} = 4kTB \left[\frac{R}{r^2} + \frac{GT(1-b)}{a^2} \right]$$

(The optimum value of τ for minimum noise, obtained by changing G , differs slightly from that for maximum responsivity.)

Substituting typical measured values for the bolometer constants in the equation above we obtain

$$W_N \simeq 3.5 \times 10^{-14} \text{ W}$$

for a bandwidth of 0.1 c/s and for $a = 0.1$. This represents the computed 'minimum detectable signal' (for which the signal-to-noise ratio is unity).

This value is some 30 times smaller than that found in practice. The reason is that no account has yet been taken of the noise originating in the amplification circuits. Almost all the noise recorded when the bolometer is in use comes from the vacuum-valve amplifier. It is not possible to say, therefore, whether or not there is an additional source of noise associated with the superconducting transition over and above the two sources considered above. If there is, it cannot be greater than about 10 times the Johnson noise.

Noise in the amplification circuits

To determine the noise which can be attributed to fundamental sources in the amplification circuits it is necessary to calculate the noise figure of the circuit, parts of which are at low temperatures. This can be done in the following way.

The circuit diagram is drawn in Figure 8(a) where the variable arms of the bridge are omitted because, being of

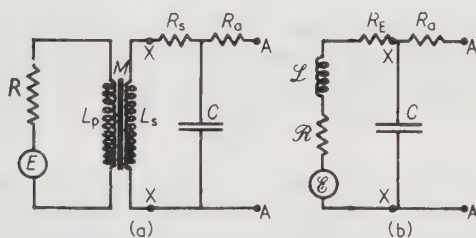


Figure 8. (a) The circuit diagram of the transformer amplifier; (b) The equivalent circuit

high resistance and in parallel with the bolometer, they do not contribute significantly to the noise characteristics. R represents the combined resistance of the bolometer and dummy resistor. The alternating e.m.f. E represents the off-balance signal from the bolometer. We wish to know the signal-to-noise ratio at the points AA which represent the input terminals of a noiseless amplifier, the noise originating in the actual amplifier being represented by the equivalent resistor R_a . The capacitance C includes the self-capacitance of the transformer's secondary, the input capacitance of the amplifier, and a capacitor introduced into the circuit to tune the secondary to the resonant condition.

All parts of the circuit to the left of the points XX are at a low temperature. Those to the right are at a high temperature because the series resistance R_s in the secondary circuit is mainly due to the constantan leads which join the transformer to the room temperature circuits (about 30 Ω). Because of this temperature difference between the two halves of the circuit it is better to consider each separately rather than construct the equivalent circuit across the points AA. We have then, using Thevenin's theorem, the equivalent circuit drawn in Figure 8(b).

$\mathcal{L}$ is equal to $[d^2/(1+d^2)]L_s$, $\mathcal{R}$ is equal to $n^2R/(1+d^2)$, and the e.m.f. $\mathcal{E}$ is $nE/(1+d^2)^{1/2}$, where d is the ratio $R/\omega L_p$ and n is the turns ratio of the transformer. We have used $M^2 = L_p L_s = n^2 L_p^2$. Because C is chosen to tune $\mathcal{L}$ to resonance it is equal to $1/\omega^2 \mathcal{L}$.

The equivalent resistance R_E represents the effects of the eddy current losses in the transformer core, and also the losses due to the capacitive effects in the secondary winding. Well-known formulae permit R_E to be expressed in terms of the permeability, resistivity, and the dimensions of the core and windings, and our measurements on the core confirm the validity of these formulae, which indicate that R_E is about 80 k Ω . The resistance of the windings and leads R_s is about 30 Ω and can be entirely neglected in comparison with R_E and $\mathcal{R}$, and is omitted from Figure 8(b).

The noise figure of a circuit may be defined as the ratio of the total mean square noise voltage at the output terminals to that part of the mean square noise which originates in the source. The resistive elements in the equivalent circuit of Figure 8(b) will each produce a mean square noise voltage proportional to the product of its resistance and its temperature. If t is the ratio of room temperature to the bolometer temperature, and noting that $\mathcal{R}$ represents the bolometer, we have for the noise figure N

$$N = 1 + \frac{1}{x} \frac{R_E}{\mathcal{R}} + \frac{t}{x} \frac{R_a}{Q^2 \mathcal{R}}$$

where $Q = \omega \mathcal{L}/(R_E + \mathcal{R})$ is the Q -factor of the secondary circuit. The numerical constant x differs from unity in order to allow for the presence of noise in the bolometer additional to the Johnson noise. It will be clear from the expressions in the previous section that, in a well-designed bolometer, the noise due to temperature fluctuations will be roughly equal to the Johnson noise, and so for these two sources alone x would be approximately 2.

The advantage from tuning the secondary circuit is shown by the presence of Q in the last term of the expression for the noise figure.

If the expression for N is expanded in terms of d with R_E , R_a , and ωL_s as constant coefficients, it can be shown that the minimum noise figure is determined by the proper choice of the ratio d , and not by either L_p or R separately. For the values of R_a , R_E , and ωL_s appropriate for our case, namely about $10^6 \Omega$, $8 \times 10^4 \Omega$, and $2 \times 10^5 \Omega$ (the maximum practicable value), respectively, we find that d should be about 4, from which it is easy to show—and

verify experimentally—that Q is approximately 1.54. Hence we find for the best noise figure:

$$N \simeq 1 + \frac{18 \times 10^4}{2.5 \times 10^4} + \frac{75}{2 \times 2.35 \times 10^4} \frac{10^6}{10^4}$$

i.e. $N \simeq 326$

The noise figure is defined in terms of the mean *square* voltage, and so the minimum detectable signal for the overall system should be approximately 18 times greater than that computed for the bolometer alone. This is found roughly to be the case. The best minimum detectable signal which we have obtained in practice is somewhat better than 10^{-12} W for a 0.1 c/s bandwidth, whereas the minimum detectable signal computed for the bolometer alone is shown in an earlier section to be about 3.5×10^{-14} W—giving a ratio of about 28.

Because the condition for minimum noise figure involves d only and not, separately, R , the bolometer resistance should be chosen for maximum signal-to-noise ratio at the bolometer. From the expression for the responsivity in an earlier section it will be seen that the signal-to-noise ratio at the bolometer is proportional to $[(1/R)(dR/dT)]^{1/2}$. Films of small resistance, though having a narrow transition, cannot have a very high value of dR/dT . On the other hand films made sufficiently thin so that R is large generally have rather broad transitions. We find that the optimum value of $[(1/R)(dR/dT)]^{1/2}$ is obtained when a bolometer is constructed with a *normal* resistance per square of about 30Ω .

Conclusion

The method of construction of the superconducting bolometers described here, and the mode of operation, permit the high detectivity of such a detector to be realized. We have not yet found means of amplification which allows the detector to be limited by its own intrinsic noise. If there are no sources of noise in the bolometer apart from the Johnson and temperature-fluctuation sources, then the present method of construction would permit a further gain in detectivity of $\times 10$ if the amplification methods could be improved.

We have also conducted experiments with bolometers constructed in a rather different way. These consist simply

of a single strand of nylon supporting an evaporated layer of tin. It was expected that their time constants would be very much shorter than those of the mica-strip bolometers, but this was not so, and there is evidence that the mechanism of detection involves not a movement along the superconducting transition curve but a change in the central fraction of the strand which is in the superconducting state compared with that at the ends in the normal state. Except when the incident power can be concentrated on an area much smaller than $3\text{ mm} \times 2\text{ mm}$, the mica-strip bolometers are more sensitive.

Finally, it should be noted that an ideal thermal detector operating within an enclosure at 4°K , and thermally linked with its surroundings only through radiative exchange, has a minimum detectable signal as low as⁹

$$W_m = 6 \times 10^{-16}\text{ W}$$

for a bandwidth of 0.1 c/s and a receiving surface of area 6 mm^2 . There remains, therefore, considerable scope for improving upon the detectivity of cooled detectors having a broad spectral band of response.

Preliminary experiments on our superconducting bolometers were conducted by Professor G. O. Jones, Dr. J. A. Hulbert, and Dr. J. L. Wilson. Dr. T. J. Dean collaborated with us in a large part of the work described in this report, and we are indebted to Mr. D. Young for his assistance in constructional problems.

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Atomic Heats of Tin and Tin-Indium

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IN a previous paper¹ (referred to below as I) a cooling method has been described in which temperatures below 1° K were obtained by the adiabatic magnetization of a superconductor. The coolants used were pure tin and tin-indium alloys. The method was used for measurements of the specific heat and in the present paper the results of this investigation are given. Since the metal is made normal in cooling, the low temperature data are those of the specific heat in the normal state and these have been supplemented by measurements in the superconductive state above 0.8° K.

Method

No further alterations to the cryostat described in I were required for making these measurements. A heater was directly wound in the middle on each specimen. The exact position of the heater with respect to the thermometer, which was at the bottom of the cylinder, did not matter in these large specimens, because with the rate of heating used, the maximum temperature difference which could occur between the extreme ends was less than 10⁻⁴ °K. The heaters were thermally connected to the specimens by means of a thin layer of surface-coating 'Araldite'. To obtain the heat capacity, we had to measure the resistance of the heater, the current through it, the time of heating, and the thermometer resistance as a function of time. The initial and the final temperatures for each heating period had to be computed from the resistance temperature calibration of the thermometer, and the heat capacity C calculated from the relation

$$C = \frac{I^2 R t}{T_f - T_i}$$

where I is the current in the heater, R the resistance, and t the time for which current was passed. The value of C thus obtained corresponded to the average temperature $\frac{1}{2}(T_i + T_f)$.

For measuring the resistance of the thermometers the circuit used was the same as that described in I. However, the galvanometer of the Wheatstone bridge was replaced by a galvanometer system employing a photocell amplifier, of the type described by MacDonald.² In a bridge circuit dealing with non-steady conditions, a necessary feature of specific heat measurements, rapid response and high damping are essential. The photocell amplifier fulfils these conditions, in addition to providing an enhanced

sensitivity. With this arrangement, changes of temperature of 10⁻⁵ °K could be easily detected. The heat supplied to the specimen was determined with a Tinsley potentiometer. To measure the time of heating, which was of the order of half a minute, a calibrated stopwatch which read to a tenth of a second was employed. In order to avoid errors in timing, this watch was operated by the heater current switch.

For the measurement of temperature, carbon resistors as described in I were used. They were calibrated against the vapour pressure of liquid helium between 2° K and 1.25° K, and from 1.25° K to 0.5° K against a magnetic susceptibility thermometer. No empirical relation was used to convert the thermometer resistance values into temperature differences. For each set of specific heat measurements, the thermometer was calibrated three times in the helium range and twice against the susceptibility thermometer. This was necessary in order to check the reproducibility of the resistance-temperature curve. By a careful spacing of the measurements in each calibration, we could obtain enough points for plotting an accurate smooth curve over the entire range, and temperature differences down to 10⁻⁴ degrees could be read directly on the graph.

The method adopted for evaluating specific heat points was the conventional one of extrapolating the temperature drifts to the middle of the heating period. Individual points were spaced at approximately 0.025° K, and temperature increments of about 0.015° K were used over most of the temperature range covered.

The errors involved in measuring the absolute temperature have been discussed in I. Errors in specific heat measurements could arise from those due to determining the temperature rise and the heating period. The temperature increments were measured to a tenth of a millidegree. This introduces an uncertainty of 0.5–1 per cent. The heating periods, about 30 sec, were measured to 0.1 sec, leading to an error of about 0.3 per cent. The potentiometer readings and the heater resistance were measured to an accuracy of at least 0.1 per cent. The heat capacities of the thermometer, the small copper vessel, the heater, and the cement used, which were neglected in our calculations, contributed not more than 0.25 per cent to the total. This figure was calculated by weighing all these separately, and using the values of the specific heats of copper, graphite, and 'Araldite'.³⁻⁵ Errors caused by the dissipation of heat

in the heater leads were avoided by coating the leads with a thin layer of lead (Pb), which remained superconducting throughout the range of measurements, both with and without the magnetic field. If the errors discussed above were all cumulative and of the same sign, the expected precision in individual specific heat points should be between 1 and 2 per cent. This estimate is confirmed by the maximum scatter in the plot of C/T against T^2 for pure tin which is about 2 per cent.

Results

(1) *Pure tin.* The sample consisted of 35 moles of tin with a purity of (99.990 ± 0.002) per cent. The experimental values of the atomic heat, in the superconducting as well as in the normal state, are given in Tables 1 and 2,

and are shown graphically in Figure 1(a). Although the lowest temperature attained on magnetization was 0.35°K , this rose to just under 0.6°K when the field was raised to 500 gauss in order to ensure the complete suppression of superconductivity. Specific heat measurements were therefore started at 0.6°K and were continued up to 2°K . Above this temperature the sensitivity of the thermometer was decreasing, so that the same degree of accuracy could not have been maintained.

The data in the normal state could be represented by the familiar expression composed of a linear and a cubic term in temperature given as

$$C_n = \gamma T + \frac{12}{5} \pi^4 R \frac{T^3}{\Theta^3}$$

Table 1. Atomic Heat of Superconducting Tin

T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)
0.800	0.191	1.156	0.853
0.832	0.230	1.178	0.961
0.875	0.277	1.210	1.056
0.893	0.304	1.236	1.190
0.928	0.343	1.255	1.259
0.958	0.368	1.308	1.419
0.980	0.400	1.405	1.84
1.003	0.461	1.570	2.60
1.025	0.513	1.650	3.25
1.048	0.520	1.741	3.85
1.070	0.597	1.845	4.49
1.093	0.670	1.937	5.34
1.114	0.736	2.057	6.19

Table 2. Atomic Heat of Pure Tin in a Field of 500 Gauss

T (°K)	C_n (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C_n (mJ.mole ⁻¹ deg.K ⁻¹)
0.604	1.104	0.865	1.67
0.632	1.142	0.881	1.68
0.655	1.220	0.912	1.76
0.673	1.260	0.930	1.78
0.692	1.286	0.966	1.88
0.710	1.335	0.989	1.94
0.727	1.375	1.021	2.05
0.742	1.378	1.057	2.15
0.757	1.43	1.079	2.21
0.769	1.45	1.118	2.30
0.783	1.52	1.183	2.49
0.798	1.52	1.245	2.64
0.817	1.54	1.470	3.39
0.840	1.60	1.653	4.07

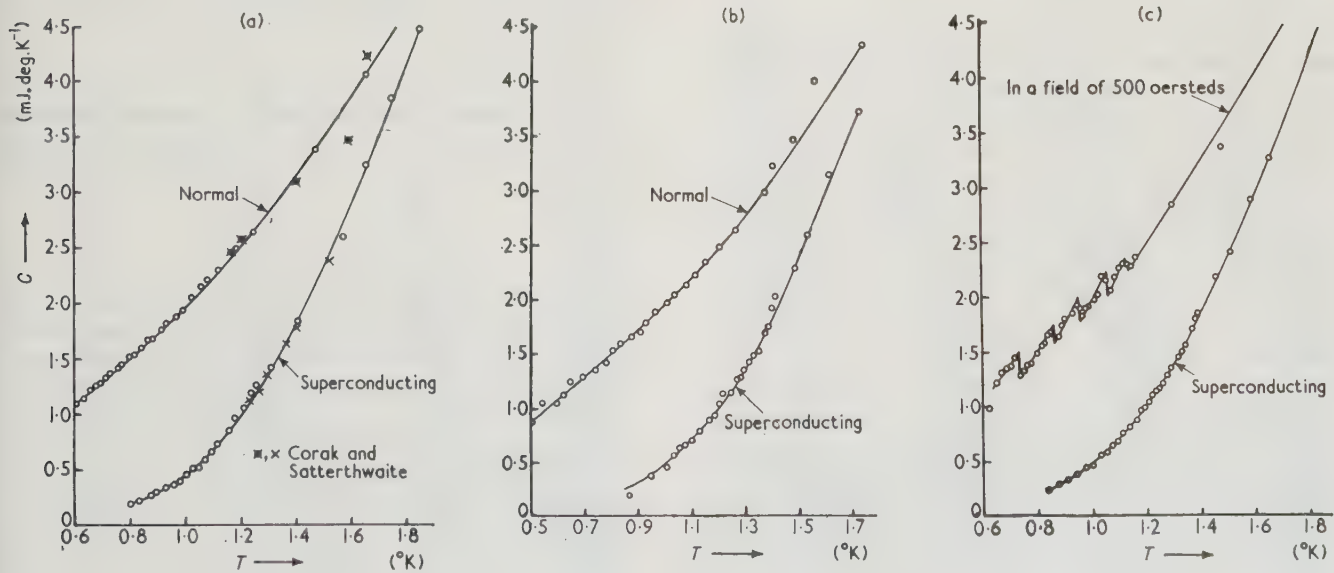


Figure 1. Atomic heat of (a) pure tin, (b) tin-1 per cent indium, (c) tin-2 per cent indium

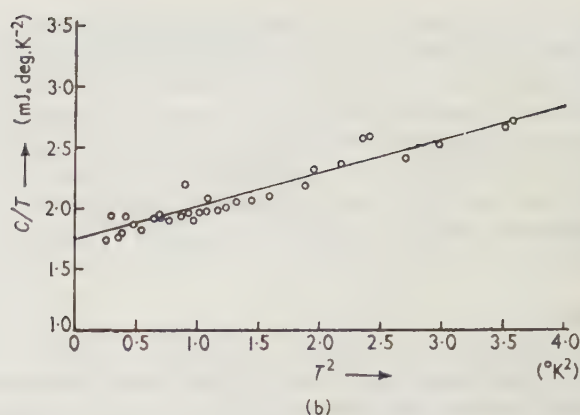
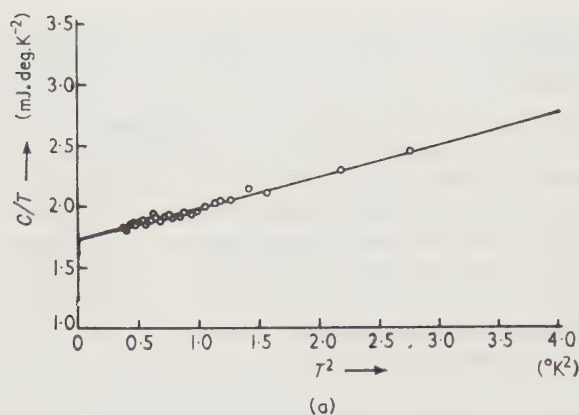


Figure 2. Curve of C/T versus T^2 for (a) pure tin, (b) tin-1 per cent indium

for the whole range of measurements. This can be seen in Figure 2(a), which is a plot of C/T against T^2 . The electronic specific heat coefficient γ and the Debye characteristic temperature Θ calculated from this graph by the method of least squares are as follows

$$\gamma = (1.727 \pm 0.008) \times 10^{-3} \text{ J.mole}^{-1} \text{ deg. K}^{-2}$$

$$\Theta = (194 \pm 1)^\circ \text{ K}$$

Comparing these values with those of Corak and Satterthwaite,⁶ which are regarded as the most accurate and which are calculated from measurements between 1.13°K and 2.5°K, we find that the agreement is within 1 per cent.

(2) *Tin with 1 per cent indium.* The data for the specific heat of a 1 per cent alloy in the superconducting state and in a field of 500 gauss are given in Tables 3 and 4 and plotted graphically in Figure 1(b). Although the experimental arrangement used for these measurements was exactly the same, the values for the normal state show greater scatter than in the corresponding curve for pure

tin. This scatter, which exceeds that to be expected from the precision of our measurements, is very marked in the plot of C/T against T^2 (Figure 2(b)). The value of γ calculated from this curve is

$$(1.729 \pm 0.016) \times 10^{-3} \text{ J.mole}^{-1} \text{ deg. K}^{-2}$$

and is the same as for pure tin except that its probable error is twice as large. Although the accuracy of our measurements is not good enough to draw definite conclusions, this value of γ is slightly lower than that of Lynton, Serin, and Zucker,⁷ who found an increase of 1.8 per cent for a concentration of 1.2 atomic per cent indium in tin. Moreover, experiments described in paper I, suggest that the greater amount of scatter in the normal values was caused by the existence of small superconducting inclusions persisting in the field of 500 gauss. As the

Table 3. Atomic Heat of Tin-Indium Alloy (1 per cent In) in the Superconducting State

T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)
0.864	0.193	1.279	1.274
0.943	0.374	1.292	1.35
1.005	0.459	1.312	1.43
1.030	0.566	1.328	1.49
1.052	0.634	1.348	1.53
1.073	0.660	1.369	1.69
1.098	0.702	1.382	1.75
1.125	0.792	1.394	1.92
1.161	0.897	1.480	2.29
1.183	0.935	1.524	2.59
1.200	1.042	1.603	3.15
1.217	1.130	1.713	3.74
1.244	1.141	1.855	4.68
1.266	1.260		

Table 4. Atomic Heat of Tin-Indium Alloy (1 per cent In) in a Field of 500 Gauss

T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)
0.505	0.879	1.035	2.04
0.542	1.052	1.078	2.14
0.597	1.050	1.110	2.23
0.623	1.123	1.148	2.35
0.647	1.250	1.200	2.48
0.693	1.297	1.260	2.64
0.741	1.352	1.368	2.98
0.780	1.42	1.396	3.23
0.806	1.54	1.471	3.47
0.828	1.61	1.530	3.93
0.835	1.61	1.549	4.01
0.875	1.66	1.641	3.94
0.909	1.70	1.722	4.33
0.928	1.79	1.872	4.96
0.945	2.08	1.882	5.10
0.963	1.89	2.055	5.77
1.006	1.97		

temperature rises, these go over to the normal state and produce discontinuous changes in specific heat. Our calculated value of γ , therefore, is not likely to be very accurate if the alloy still contains superconducting material.

(3) *Tin with 2 per cent indium.* Specific heat measurements for the superconducting state and in a field of 500 gauss were also made on a tin with 2 per cent indium specimen. If our assumption of the persistence of superconducting material at low temperatures in a field greater than the critical value for the pure metal was correct, its influence should be more evident in the specific heat determinations of this specimen. For this reason we decided to make individual determinations of specific heat points at slightly closer temperature intervals. The results are given in Tables 5 and 6, and have been plotted in Figure 1(c). The discontinuities in the normal curve at various temperatures are very distinct and are well above the scatter of individual points. It is well known that impurities in a superconductor generally tend to form a sponge-like network of increased critical value and that magnetic flux enters abruptly into the material enclosed in the mesh as the temperature is raised.⁸ The irregularities observed in the normal specific heat are evidently due to the thermal effects associated with this mechanism.

The electronic specific heat in the superconducting state

According to Bardeen, Cooper, and Schrieffer,⁹ the molar electronic specific heat in the superconducting state is given by

$$\frac{C_{es}}{\gamma T_c} = \frac{3}{2\pi^2} \left(\frac{\epsilon_0}{kT_c} \right) \left(\frac{T_c}{T} \right)^2 [3K_1(\beta\epsilon_0) + K_3(\beta\epsilon_0)] \quad \dots (1)$$

where γT_c is the electronic specific heat in the normal state at the transition temperature T_c , ϵ_0 is the half-width of the energy gap in the single particle density of states, k is the Boltzmann constant, K_1 and K_3 are the modified Bessel functions of the second kind, and β is $1/kT$. It is assumed that $\beta\epsilon_0 \gg 1$.

The curve obtained from equation (1) by calculating the values of $\log_{10}(C_{es}/\gamma T_c)$, shown in Figure 3(a), has a slight downward curvature. However, for T_c/T between 2.5 and 5.5 it can be closely approximated by a straight line which satisfies the equation

$$\frac{C_{es}}{\gamma T_c} = a \exp \left(\frac{-bT_c}{T} \right) \quad \dots (2)$$

where $a \simeq 8.5$ and $b \simeq 1.44$. It has been found that, in the case of several superconducting metals including tin, the experimental data can be represented fairly well by equation (2) and that for tin the values of a and b are 9.17 and 1.5, respectively. Recently, however, Boorse¹⁰ has pointed out that there exist definite deviations from the above approximation, particularly in the region $T_c/T \geq 4$. In deriving the exponential law, Bardeen, Cooper, and Schrieffer have used a constant electron-electron interaction. But Cooper¹¹ has shown that if one uses an electron-electron interaction which is non-constant and aniso-

Table 5. Atomic Heat of Tin-Indium Alloy (2 per cent In) in the Superconducting State 3.4

T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)
0.837	0.239	1.245	1.156
0.875	0.294	1.258	1.210
0.909	0.333	1.275	1.293
0.940	0.385	1.291	1.352
0.974	0.447	1.304	1.282
1.000	0.466	1.316	1.45
1.029	0.554	1.329	1.50
1.052	0.583	1.342	1.56
1.072	0.645	1.354	1.57
1.091	0.683	1.366	1.71
1.110	0.755	1.377	1.80
1.138	0.812	1.388	1.85
1.147	0.806	1.455	2.19
1.162	0.878	1.510	2.41
1.178	0.969	1.585	2.89
1.193	0.999	1.655	3.26
1.207	1.040	1.764	3.70
1.220	1.104	1.896	5.07
1.233	1.139		

Table 6. Atomic Heat of Tin-Indium Alloy (2 per cent In) in a Field of 500 Gauss

T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)	T (°K)	C (mJ.mole ⁻¹ deg.K ⁻¹)
0.622	0.995	0.946	1.93
0.652	1.220	0.957	1.90
0.669	1.310	0.966	1.83
0.688	1.356	0.977	1.91
0.704	1.37	0.988	1.91
0.719	1.45	1.011	1.98
0.737	1.29	1.024	2.03
0.751	1.33	1.038	2.19
0.765	1.38	1.054	2.15
0.778	1.40	1.070	2.06
0.800	1.49	1.085	2.18
0.817	1.57	1.100	2.27
0.827	1.58	1.116	2.30
0.838	1.66	1.132	2.30
0.848	1.68	1.147	2.28
0.858	1.66	1.162	2.37
0.868	1.60	1.296	2.84
0.879	1.64	1.468	3.26
0.889	1.74	1.478	3.37
0.899	1.80	1.738	4.59
0.909	1.82	1.800	4.63
0.930	1.86		

tropic, as is the case in actual metals, the energy of a single-particle excitation depends on the direction as well as the magnitude of its momentum vector. The idea of the anisotropy of the energy gap in pure metals has also been discussed independently by Pippard and Heine.¹² According to Cooper,¹¹ the variation in the energy gap can manifest itself as a deviation from the exponential law assumed

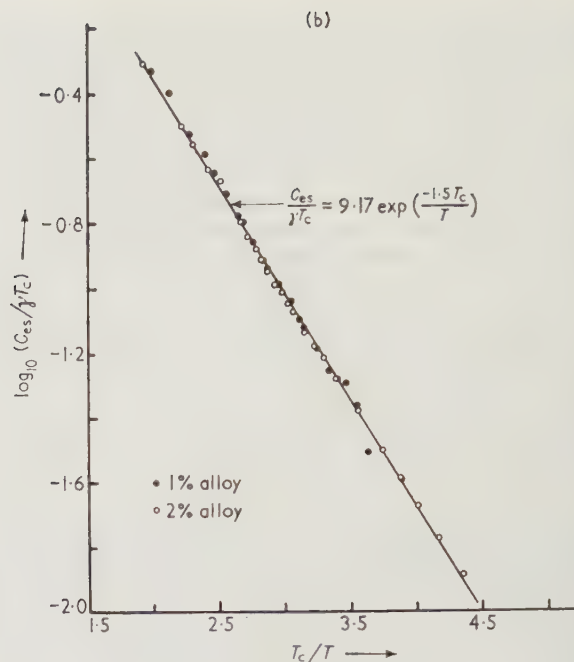
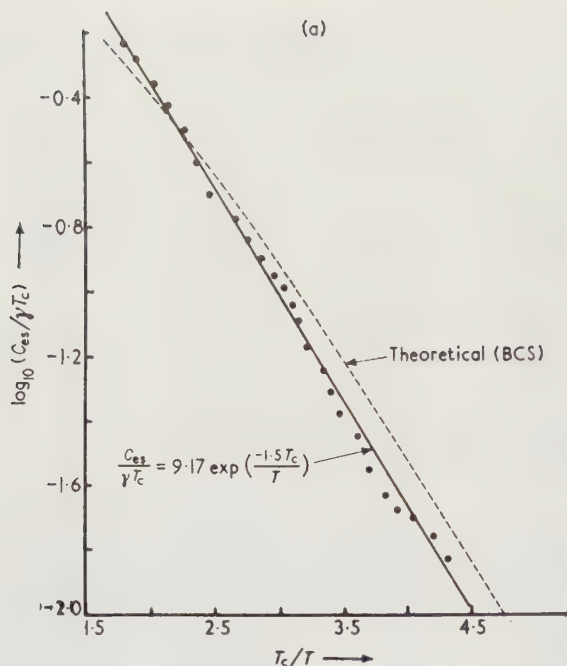


Figure 3. Curve of $\log_{10} (C_{es}/\gamma T_c)$ versus T_c/T for (a) pure tin, (b) tin-1 and 2 per cent indium

for the superconducting electronic specific heat. The situation in the case of alloys, however, is different. Anderson¹³ in his theory of dirty superconductors shows that owing to scattering from physical and chemical impurities the interaction responsible for the superconducting properties in alloys is a constant because it has to be averaged over the entire Fermi surface. This results in the disappearance of the anisotropy in the energy gap. The original Bardeen, Cooper, and Schrieffer theory is therefore more nearly correct in the case of superconducting alloys than it will be for pure superconductors, and the exponential law should be obeyed by alloys more exactly than by pure metals.

In Figure 3(a) and (b) we have plotted $\log_{10}(C_{es}/\gamma T_c)$ against T_c/T for pure tin and tin-indium alloys of 1 and 2 per cent concentrations. It can be seen that for T_c/T between 2 and 4.5 the alloys follow the straight line much better than pure tin, which shows deviations greater than expected from the experimental errors involved in our measurements. C_{es} in all the three cases has been obtained by subtracting the lattice contribution C_{lat} from the total specific heat in the superconducting state. C_{lat} is calculated from the value of Θ obtained above, and is assumed to remain unchanged by the onset of superconductivity. Owing to the irregularities in the normal state specific heat mentioned above, the values of γ used for the alloys have been calculated from the formula given by Doidge.¹⁴ Their transition points, which are required for this, were measured by heating the specimens in zero field at a constant rate and measuring the temperature at which a discontinuity appeared in the rate of warming.

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Multiple Layer Insulation for Cryogenic Applications

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THE storage and transport of large quantities of cryogenic fluids is rapidly becoming an important activity. Techniques for insulating the associated equipment are progressing with profound success. Vessels for storing liquid hydrogen and helium are always carefully insulated, usually with an evacuated insulation. Less stringent requirements apply to vessels for nitrogen, oxygen, and other liquids with higher boiling points and higher volumetric heats of vaporization. However, the same general rules and techniques apply to the insulation of any cryogenic device. The insulation to be described (multiple layer insulation, super-insulation, maximum efficiency insulation, or super-Dewars)¹⁻⁷ constitutes a new technological development of some old ideas.

In 1898, Dewar⁸ pointed out that he could reduce the heat transport to the inner container of his vacuum flasks by inserting multiple reflecting surfaces between the hot and cold walls. Since that time the reduction of radiation heat transfer using multiple radiation shields has been studied extensively.⁹ The heat transport through a large number of multiple floating radiation shields is reduced approximately as the inverse of the number of radiation shields. However, the suspension of a large number of floating shields having extremely close spacing seems to be an engineering impossibility. A break-through in the technology of cryogenic insulation occurred when a practical method of spacing aluminium foil shields with very fine glass wool sheets (in high vacuum) was reported by Petersen¹⁰ in 1951. The promise of reducing the rate of evaporation in a cryogenic vessel by as much as a factor of 20 over ordinary evacuated powder insulations, for a given thickness, has stimulated great interest in this new method. Many cryogenic organizations are actively striving to develop insulations having the lowest possible heat transport. These insulations are particularly advantageous when 'payload' is extremely important or when it is desirable to keep the insulation moderately thin. We have developed a highly efficient insulation (Petersen type) using thin aluminium foil separated by glass-fibre paper.¹¹

Theory

The heat transport through multiple layer insulation arises from gas conduction, solid conduction, and radiation. (1) The heat transport due to gas conduction decreases with the absolute pressure^{12, 13} at low pressure and becomes negligible at pressures below 0.1 micron. (2) The

heat transport due to conduction through a system consisting of alternating layers of dissimilar materials cannot be treated with complete rigour. The heat transport through any continuous solid portion of the material can be expressed in terms of the Fourier¹⁴ equation. However, the conductance across the shield-spacer interface or between touching strands of the spacer material has been treated to a very limited extent.¹⁵ (3) The radiation contribution can be expressed in terms of the Stefan-Boltzmann¹⁶ equation. If the spacer materials are assumed to be transparent, and if the emissivity of the boundaries and shields are the same, the radiant energy transfer will be proportional to the emissivity and to the number of regions into which the shields divide the insulation space. No expression has been derived that will take into account the radiation heat transport when the spacer material is not transparent.

The heat transfer through multiple layer insulation is arbitrarily expressed in terms of an effective thermal conductivity derived from the Fourier equation. However, this is only a convenience and should not imply that the radiation contribution is negligible. On the contrary, available information indicates that perhaps 30 per cent or more of the total heat through this type of insulation is by radiation, although the percentage will be dependent upon the boundary temperature and the temperature distribution throughout the sample.

Although this new combination of materials has a remarkably low thermal conductivity it is not a panacea for all insulation problems. The components required for manufacture are relatively expensive and in many instances the application is difficult and therefore expensive.

The heat transport due to radiation between two parallel plane surfaces with n interposed floating shields of effective emissivity E has a net exchange of radiant energy W_r given by¹⁷

$$W_r = \frac{E\sigma A}{n+1}(T_2^4 - T_1^4) \quad \dots (1)$$

where A is the area, σ the Stefan-Boltzmann constant, and T_2 and T_1 are the temperatures of the hot and cold boundaries, respectively. More general forms of this relation have been derived for cases when the hot and cold surfaces are not parallel planes or when the emissivities of the boundaries are not equal to the emissivities of the shields.¹⁷

Figure 1 shows the theoretical temperature distribution for radiation shields separated by a vacuum between parallel walls at 300°K and 76°K, and parallel walls at 300°K and 4°K. The curves were obtained from the relation

$$\frac{T_i}{T_2} = \left\{ 1 - \frac{i}{n+1} \left[1 - \left(\frac{T_1}{T_2} \right)^4 \right] \right\}^{1/4} \quad \dots (2)$$

where T_i is the temperature of the i th shield and i is the number of the i th shield counting from the warm wall (T_2). The cold wall temperature (T_1) is taken as 77°K and 4°K in the Figure.

Fourier's equation for the steady-state one-dimensional conduction of heat through a single homogeneous solid of constant cross-sectional area can be written as

$$W_c = \frac{kA(T_2 - T_1)}{t} \quad \dots (3)$$

where k is the mean thermal conductivity between the two temperature boundaries and t is the sample thickness.

The total heat transport through a sample of multiple layer insulation can be expressed as

$$W_T = W_r + W_c + W_i \quad \dots (4)$$

where W_i arises from the interaction between radiation and conduction. So far it has not been possible to separate W_r and W_c with any degree of accuracy or to estimate the magnitude of W_i from the existing experimental data.

It is convenient to express the results in terms of an average mean thermal conductivity k_a derived from the following equation

$$W_T = \frac{k_a A(T_2 - T_1)}{t} \quad \dots (5)$$

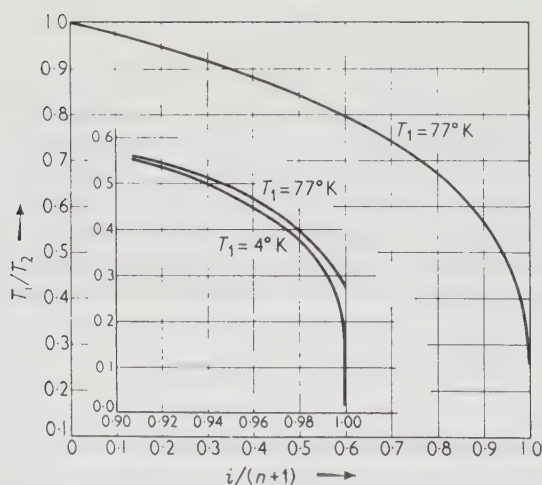


Figure 1. Temperature distribution through a system of n floating radiation shields; i denotes any shield between 1 and n , $T_2 = 300^\circ\text{K}$ is the warm boundary temperature, and T_1 is the cold boundary temperature

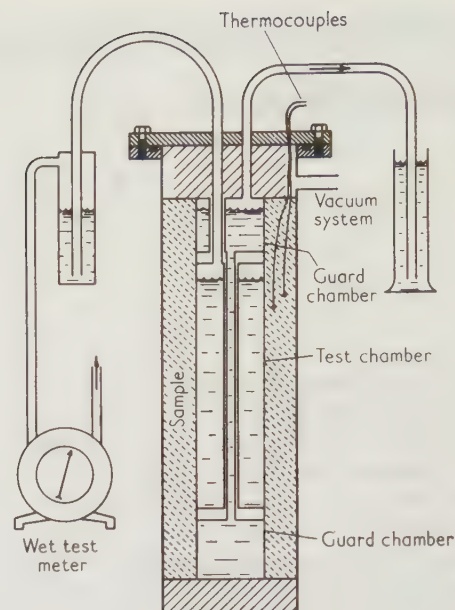


Figure 2. Schematic drawing of the test calorimeter

Thus, our results will be expressed in terms of k_a between specified temperature boundaries.

Apparatus

Figure 2 shows a schematic drawing of the calorimeter used for testing multiple layer insulation. The test and guard chambers are 4 in. diameter hollow cylinders that form a mandrel for wrapping the insulation. These chambers are filled with cryogenic fluid and form the cold boundary during the tests. Thermocouples used to measure the temperature distribution are suggested in the Figure. The vacuum chamber is connected to the vacuum pumping system and the seal between the top plate and the outer container is made by a 'Neoprene' O-ring.

The test chamber is vented through a wet test meter. The rate of evaporation is directly proportional to the rate of heat transport through the sample. The guard chambers are vented through a column of water in order to make the guard chamber temperature slightly higher than the test chamber temperature. This avoids condensation of the test chamber vent gas as it passes through the guard.

The apparent mean thermal conductivity k_a for this experimental arrangement is given by

$$k_a = \frac{W_T \ln(r_o/r_i)}{2\pi l(T_2 - T_1)} \quad \dots (6)$$

where W_T is the rate of heat transport to the test chamber, l is the length of the test chamber (18 in.), and r_i and r_o are the inside and outside radii of the specimen, respectively.

The overall accuracy of measurement is estimated to be better than ± 5 per cent if care is taken to wait for complete equilibrium. Some factors that can cause large errors are

(1) non-equilibrium conditions caused by rapidly changing barometric pressure, (2) oxygen concentration in the liquid nitrogen, and (3) uncalibrated wet test meters. Our experiments indicate that the accuracy of measurement is greater than the reproducibility in sample fabrication.

The apparatus shown in Figure 2 can give erroneous results if it is not used in the proper manner. For example, when aluminium shields are used in sample fabrication a sizeable axial conduction can exist if the ends of the sample are not guarded. When a radiation shield was placed across the lower end of the test calorimeter, without touching the sample, the apparent conductivity changed from 0.5 to 1.1 $\mu\text{W}/\text{cm}.\text{deg}.\text{K}$ as the radiation shield temperature changed from 76° K to 300° K. These results indicate that the guard chambers are not completely effective and that the ends of the sample must be carefully insulated.

Procedure

Alternate layers of insulating and reflecting material were wrapped on the test and guard chambers of the apparatus shown in Figure 2. The insulation material was wrapped in a continuous spiral whereas the reflector material (i.e. aluminium foil) was interrupted after each revolution to eliminate conduction around the spiral. Table 1 gives the specifications of the material used for

Table 1. Specification of Materials Used to Fabricate Samples

1. Fibre glass paper, 0.02 cm thick, 95 % AAA fibre (av. dia. 0.00005 cm), Dexter Paper Co.
2. Fibre glass paper, 0.012 cm thick, 95 % AAA fibre, Dexter Paper Co.
3. 'Fiberglas' mat, 0.02 cm thick, polystyrene bond, Owens Corning
4. Fibre glass, 108 mat, AA fibre (av. dia. 0.00011 cm), Libby-Owens-Ford
5. Nylon net, 0.015 cm thick, 90 % void
6. Glass fabric, 0.01 cm thick, plain weave, Trevano
7. Aluminium foil, 0.00127 cm or 0.00058 cm thick, Alcoa
8. 'Mylar', 0.00127 cm thick, aluminized one side to 10 % transmission, Dobeckmun
9. 'Mylar', 0.00127 cm thick, aluminized both sides, Dobeckmun

fabrication of our samples. The test results were nearly independent of aluminium foil thickness 0.00125 or 0.000575 cm. Therefore, throughout the following sections the term 'foil' will refer to either of these two thicknesses.

After wrapping, the samples were inserted into the vacuum chamber and evacuated. During evacuation the sample temperature was maintained at approximately 100° C for about 3 days to help drive the residual moisture from the sample. The guard and test chambers were then filled with cryogenic fluid, either hydrogen or nitrogen, and the rate of liquid evaporation measured with a wet test meter and timer. The gas pressure in the samples during the tests was always less than 0.01 micron. The time required for steady state conditions varied from 1 to 3 days depending upon the heat flux through the sample and upon the rate of change of barometric pressure.

Results and discussion

Fibre glass paper and aluminium foil. The lowest values of thermal conductivity were obtained using fibre glass paper separated by layers of aluminium foil. These results are shown in Table 2. The heat transport through multi-layer samples is very sensitive to the tightness of the wrap.

Table 2. The Apparent Mean Thermal Conductivity of Fibre Glass Paper-Aluminium Foil Insulation. Results of 12 representative tests

Sample number	Fibre glass thickness (mils)	Sample thickness (cm)	Number of shields (per cm)	Density (g/cm ³)	Cold wall (T°K)	k_a ($\mu\text{W}/\text{cm}.\text{deg}.\text{K}$)
1	8	3.3	22	0.16	76	0.55
					20	0.4
2	8	3.8	20	0.14	76	0.5
					20	0.4
3	8	2.5	20	0.14	76	0.7
					20	0.6
4	8	3.0	20	0.18	76	1.3
5	4.8	3.8	30	0.13	76	1.0
6	4.8	4.3	14	0.06	76	0.7
Calorimeter (Figure 3)						
7	8	1.9	24	0.18	76	1.4
8	4.8	1.9	21	0.09	76	0.9
					20	0.5
Estimated best values (loosely applied sample)						
	4.8		20-50	0.1	76	0.6
					20	0.5
(firm sample)						
	4.8		70-100		76	2-5
					20	2-5

We observed conductivity variations from 0.55 to 3.5 $\mu\text{W}/\text{cm}.\text{deg}.\text{K}$ between 300° K and 76° K arising from compaction. Accidental variations in conductivity from 0.5 to 0.8 were observed in samples of the same material and approximately the same tightness of wrap. This variation was attributed to slight differences in compaction. Pure fibre glass paper has a k_a of about 5 $\mu\text{W}/\text{cm}.\text{deg}.\text{K}$ between 300° K and 76° K. A tightly wrapped multiple layer sample is expected to have approximately the same value.

The experimental results (Table 2) show the sample thickness, number of shields, sample density, and cold boundary temperature. The warm boundary was always maintained at ambient temperature (approx. 300° K). The apparent mean thermal conductivity between ambient temperature and the specified cold boundary temperature was computed from equation (6) and is shown in the last column.

The results from both the test calorimeter and a 60 l. Dewar (Figure 3) are shown in Table 2. As the results

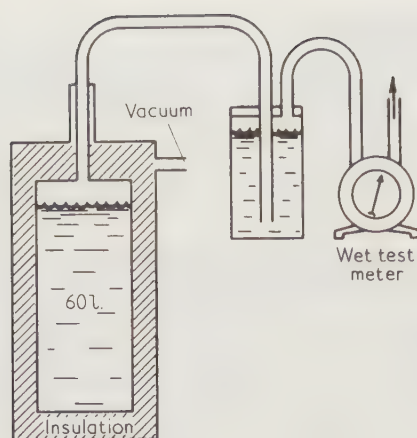


Figure 3. Schematic drawing of the 60 l. test vessel

from the two pieces of apparatus are in substantial agreement, the estimated best results for aluminium foils separated by fibre glass paper are tabulated.

Effect of spacer material. Other low conducting spacer materials were used to separate the aluminium foil shields. These results are shown in Table 3.

Table 3. The Apparent Mean Thermal Conductivity of Some Selected Multiple Layer Insulations. Aluminium Foil Spaced with Various Materials

Sample thickness (cm)	Number of shields (per cm)	Density (g cm ³)	Cold wall (T°K)	k_a ($\mu W/cm.deg.K$)	Spacer material (Table 1)
3.7	26	0.12	76	0.7	3. 'Fiberglas' mat
			20	0.5	
2.5	24	0.09	76	2.3	5. Nylon net
1.5	76	0.76	76	5.2	6. Glass fabric
Calorimeter (Figure 3)					
4.5	6	0.03	76	3.9	4. Fibre glass
2.2	6	0.03	76	3.0	4. Fibre glass

The 'Fiberglas' mat is a very efficient separator. It has relatively high mechanical strength due to application of a binder. This binder (styrene, starch, or phenolic) is objectional in a vacuum system.

When nylon net is substituted for the glass paper the conductivity increases by a factor of about 3. This is attributed to the increased thermal conductivity of the nylon fibres, large fibre diameter, and to the lack of contact resistance between the individual fibres.

The conclusions derived from the nylon net experiments are substantiated in part by the results on the glass fabric sample. The fabric was made from large fibre material bonded together with a binder.

Pure unmatted fibre glass (Table 1, sample 4) with its fibres aligned perpendicular to the direction of heat flow

was expected to give the lowest ultimate thermal conductivity. The relatively high heat transport through our samples made from this material is due to the small number of shields per unit thickness. In our test calorimeter we were never able to obtain more than about 6 shields/cm.

Effect of reflector material. Aluminized 'Mylar' was used in place of aluminium foil to separate the fibre glass paper. These results are shown in Table 4. These samples

Table 4. The Apparent Mean Thermal Conductivity of Samples Using Aluminized 'Mylar' as the Reflector Material

Sample thickness (cm)	Number of shields (per cm)	Density (g/cm ³)	Cold wall (T°K)	k_a ($\mu W/cm.deg.K$)	Spacer material (Table 1)
2.5	14	0.06	76	2.4	4. Fibre glass
4.3	9	0.03	76	2.0	2. Fibre glass paper

have a comparable or slightly higher conductivity than equivalent samples using aluminium foil. It may be possible to lower the conductivity of this type of material by imposing very loose separation.

Metallized plastic. Table 5 shows the results of using aluminized 'Mylar' with no spacer material. The sample

Table 5. The Apparent Mean Thermal Conductivity of Aluminized 'Mylar'

Sample thickness (cm)	Number of layers (per cm)	Density (g/cm ³)	Cold wall (T°K)	k_a ($\mu W/cm.deg.K$)	Note
3.5	24	0.045	76	0.85	'Mylar' aluminized one side
1.3	47	0.09	76	1.8	

was wrapped very loosely (24 layer/cm of 0.00127 cm thick 'Mylar'). After testing, it was compacted to a higher density (47 layer/cm) by surrounding it with a split metal cylinder and squeezing down on it. The conductivity increased from 0.85 to 1.8 $\mu W/cm.deg.K$.

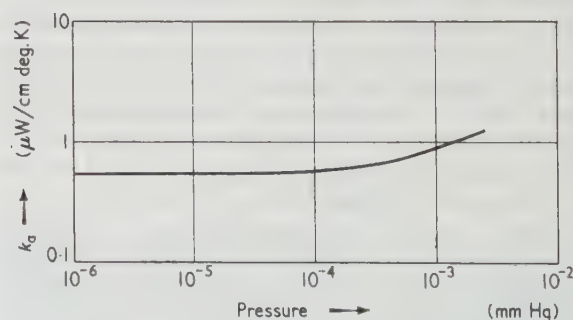


Figure 4. Dependence of the apparent mean thermal conductivity on interstitial nitrogen gas pressure. Boundary temperatures 300 and 76° K

Effect of interstitial gas pressure. The effect of interstitial gas pressure upon the thermal conductivity of a glass paper-aluminium foil sample (Table 2, sample 1) is shown in Figure 4. The results show that below 0.1 micron of mercury the heat transport is independent of interstitial gas pressure. The conductivity is the mean conductivity between 300°K and 76°K with nitrogen as the interstitial gas.

Effect of sample compression. It is interesting to consider multiple layer insulation as a support for the inner shell of a Dewar vessel, heat transport due to support members thus being reduced to zero. With this problem in mind we measured the stress-strain curve of a stack of fibre glass paper and aluminium foil and the result is shown in Figure 5. This result does not mean very much unless we know

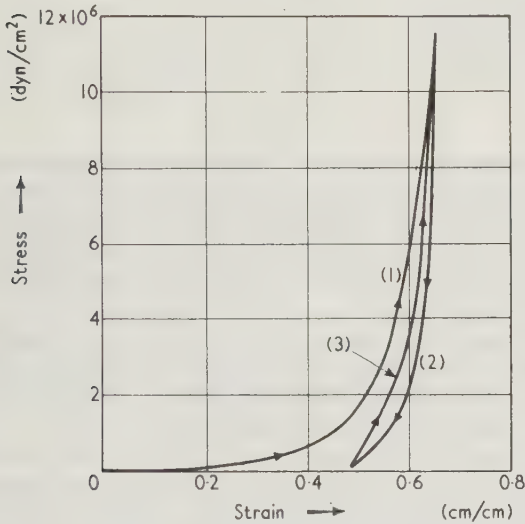


Figure 5. Stress-strain curve of the insulation described in Table 2. The original stack of 160 layers of paper and 160 layers of foil was pre-loaded 6.9×10^4 dyn/cm²

how the conductivity varies with applied stress. The best estimate we can make from existing data is that the conductivity varies from about 0.5 to 1.0 μ W/cm.deg.K for loosely packed material and from 3.0 to 5.0 for compressive loads at 0.5 to 1.0×10^6 dyn/cm².

Sample temperature distribution. The heat transport due to conduction and that due to radiation is not readily separable as ascertained from the experimental data. Figure 6, curve (a), shows the measured temperature distribution through a typical sample (Table 2, sample 4). Curve (b), obtained from Figure 1, shows the temperature distribution expected if each sheet of aluminium foil was a floating radiation shield. Curve (c) shows the computed temperature distribution through a sample having a temperature-independent thermal conductivity. The observed result is probably due both to the presence of radiation and the fact that the thermal conductivity of glass varies with temperature. The thermal conductivity

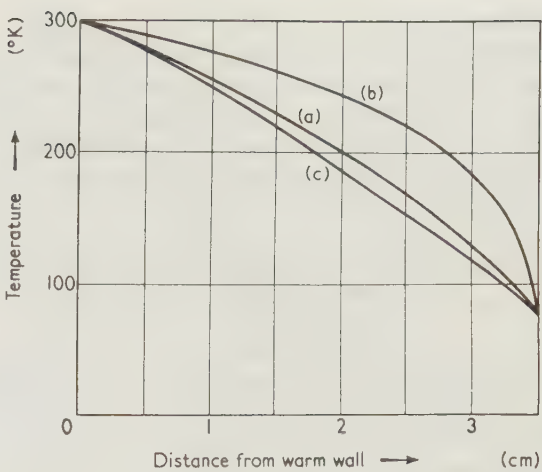


Figure 6. Temperature distribution through a typical sample: (a) Experimental; (b) Theoretical (Figure 1); (c) Ideal Fourier conduction with constant k

of most disordered dielectrics is approximately proportional to the temperature, but the temperature dependence of contact resistance is not well understood.

A crude estimate of the heat transport through a typical sample due to radiation can be made in the following manner. Let us assume:

- (1) The emissivity (ϵ) of the aluminium foil is 0.04;
- (2) The total heat transport is a linear sum of radiation and conduction, i.e. equation (4) with $W_i = 0$;
- (3) Each radiation shield is floating.

Then, from equation (1) we find that about 20 to 40 per cent of the total measured heat transport in our best samples can be attributed to radiation.

Spaces between adjacent shields at a corner or joint can add significantly to the total heat transport. Figure 7 shows a schematic representation of a sample containing 3 butt joints. Strips of fibre glass paper were separated by aluminium foils and applied in bats 0.64 cm thick to the calorimeter shown in Figure 3. Each adjacent bat was adjusted axially, as shown, so that the joint was continuous for only 0.64 cm. This procedure was used to construct a sample of 4.5 cm thickness, 9 joints, and having a density of 28 layers/cm. The conductivity was 3.0 μ W/cm.deg.K. This constitutes about a four-fold increase in the total heat transport due to the 9 joints.

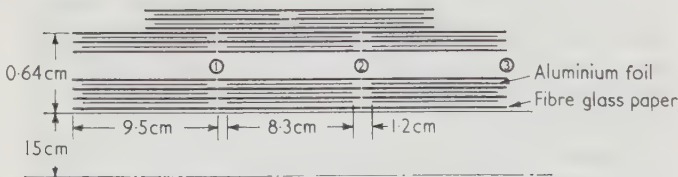


Figure 7. Schematic drawing of a sample fabricated to study the effects of joints

Applications

A significant saving of liquid nitrogen or liquid oxygen can be accomplished by using multiple layer insulation in place of high vacuum or evacuated powder. However, quite frequently the cost of installation and maintenance does not justify its use to conserve these relatively inexpensive fluids. Table 6 shows the heat transfer between

Table 6. Heat Transfer Through 2.54 cm of Typical Cryogenic Insulations (in $\mu\text{W}/\text{cm}^2$)

Density (g/cm^3)	High vacuum (emissivity = 0.02)	Multiple layer	Evacuated powder ¹⁸
Boundary temperatures (°K)	0	0.1	0.07
300	910	70	260
76			
300	920	55	220
20			
300	920	47	170
4			

parallel walls for three types of cryogenic insulation, (1) high vacuum, (2) multiple layer, and (3) silica aerogel plus aluminium powder.¹⁸ Justification for using multiple layer insulation must be made for each specific application.

Shipment of helium and hydrogen. Large containers for the transport of liquid hydrogen and helium have been constructed using multiple layer insulation.^{4, 19} Where the payload is valuable and the insulation space is limited (i.e. road transportable containers) this type of insulation may be very advantageous. The low thermal conductivity makes it possible to construct a container for the shipment of liquid helium for gaseous use on a no-loss basis. (The term 'liquid' helium is not strictly true because these containers are allowed to pressurize above the critical pressure.) Table 7 shows the economics of shipping helium as a compressed gas and as a liquid.²⁰ For large-scale shipments the container weight for the shipment of liquid is about one-sixteenth that of the container required for shipping the same mass of gas at high pressure. Thus, this saving in weight results in a great saving in shipping cost.

It should be pointed out that a relatively large thickness (30 to 60 cm) is required before multiple layer insulation becomes superior to a good nitrogen-shielded high vacuum vessel.

Transfer lines. A simulated vacuum-insulated transfer line with a 7.95 cm diameter inside line was insulated by van Gundy²¹ with multiple layer insulation of the type shown in Table 4. The apparatus was similar to the one shown in Figure 2.

Figure 8 shows the complete results of these tests. Curve (a) is the heat flux as a function of interstitial gas pressure for high vacuum insulation. Curve (b) is the heat flux through 2.5 cm of multiple layer insulation.

Table 7. A Comparison of Container Weight per Amount of Helium Shipped for Cryogenic and Non-cryogenic Shipping Techniques²⁰

Container	Gross weight (lb)	Amount of helium (ft^3 n.t.p.)	(gross wt/1,000 ft^3)
High pressure railroad car	225,000	260,000	865
High pressure cylinders	125	210	595
50 l. Dewar, N_2 shield (high vacuum)	350	1,250	280
750 l. vessel, multiple layer insulation, no N_2 shield	1,300	18,600	70
27,000 l. vessel, multiple layer insulation, no N_2 shield	35,000	670,000	52

The initial heat flux to the inner line at 20° K (before the application of the insulation) was $1.3 \times 10^{-3} \text{ W}/\text{cm}^2$. The application of 2.5 cm of multiple layer insulation reduced the heat flux to $2.5 \times 10^{-4} \text{ W}/\text{cm}^2$. The use of the best insulation shown in Table 2 would reduce the heat flux to $5.5 \times 10^{-5} \text{ W}/\text{cm}^2$.

The heat flux through the multiple layer sample is independent of the two initial conditions investigated, (1) high vacuum, and (2) 6 lb/in² (gauge) of carbon dioxide in the vacuum space at room temperature.

Multiple layer insulation not only lowers the total heat flux but increases the pressure at which gas conduction starts to become an effective heat transfer mechanism. This effect allows a closed system to de-gas more and thus lengthens the useful life of the line.

Summary

The heat transfer through multiple layer insulation at cryogenic temperatures is significantly less than through

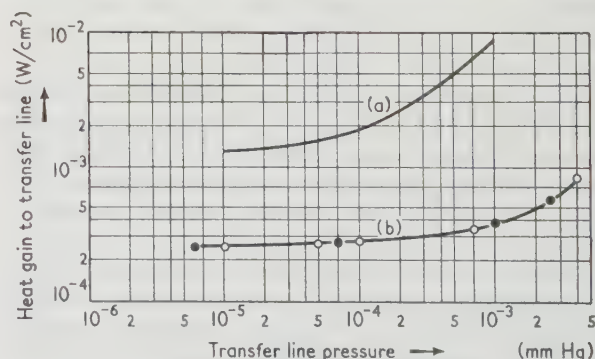


Figure 8. Heat transfer to a simulated transfer line: (a) High vacuum insulation; (b) Multiple layer insulation (○ = with high vacuum; ● = with carbon dioxide at 1.4 atm and 300° K)

any other type of insulation. Our best results have been obtained using aluminium foil separated by layers of fibre glass paper. However, many other choices of reflector and insulation materials may be used to advantage under specific applications. The cost of this insulation is relatively high both in material and in man-power used in its application. The justification for its use has to be evaluated in terms of its ultimate saving of cryogenic fluid or insulation weight.

Its use makes possible the storage of liquid helium without the requirement of a liquid nitrogen shield. It can also be used for the insulation of large-size liquid transfer lines.

Multiple layer insulation is being used for many applications in cryogenic engineering. Among these, its use in the missile and space exploration field should be included. Its high insulating qualities and relatively low density make it ideal for this purpose. Future requirements of the space age could rely heavily on this type of material.

The author wishes to acknowledge the help of Mr. M. M. Fulk and Mr. J. E. Schrodt in the preparation of this manuscript.

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CONFERENCES

The 1961 *Cryogenic Engineering Conference* will be held on 15-17 August at Ann Arbor, Michigan. Abstracts (of not more than 200 words) of papers to be read and a preliminary manuscript should be sent before 1 May 1961 to: The Conference Secretary, Prof. K. D. Timmerhaus, Cryogenic Engineering Conference, Chemical Engineering Department, University of Colorado, Boulder, Colorado, U.S.A. Further details are obtainable from him.

The proposed dates of meetings of Boards and Commissions of the *International Institute of Refrigeration* are: Technical Board, 14-16 September 1961, London; Commission 1, 20-22 September, London (details from Dr. K. Mendelssohn, Oxford); Commissions 2, 3, and 8, 20-22 September, Cambridge; Commission 9, 14-16 September, London.

The *International Conference on Magnetism and Crystallography* will be held by invitation of the Science Council of Japan on 25-30 Sep-

tember 1961. Part 1 (Magnetism) will be under the chairmanship of Prof. T. Nagamiya, and will have the co-sponsorship of the International Union of Pure and Applied Physics. Part 2 (Crystallography) will be under the chairmanship of Prof. Niyake of the University of Tokyo, and will have the co-sponsorship of the International Union of Crystallography. Further particulars may be obtained from: The Chairman of the Organising Committee of the International Conference on Magnetism and Crystallography, Science Council of Japan, Ueno Park, Tokyo, Japan. (Cables to: SCIENCOUNCIL, TOKYO.)

The *International Calorimetry Conference* will be held on 14-17 August 1961 at Ottawa. The programme chairman is: Dr. J. E. Kunzler, Bell Telephone Laboratories Inc., Murray Hill, New Jersey, U.S.A. Abstracts (of not more than 250 words) must be received by him by 15 May.

A Pressure Cryostat with Continuous Refill[†]

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WITH a pressure cryostat, using a boiling liquid, a wide temperature range can be covered which can be extended nearly as far as the critical point (cf. reference 1). A wider application is, however, limited by the facts that the heat of evaporation per cubic centimetre diminishes with rising temperature and, above all, that refilling of the cryogenic liquid is difficult. For these reasons pressure cryostats have found relatively little use although, with neon for instance, temperatures between 27 and 43° K and, with methane, between 112 and 180° K are accessible. On the other hand, the advantages can be fully exploited when continuous refill action is possible without upsetting the temperature equilibrium of the system. This paper describes such a cryostat (Figure 1).

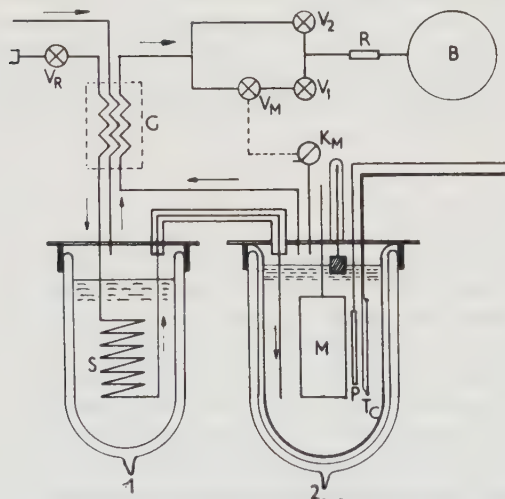


Figure 1. Flow diagram of the pressure cryostat

A flow of gas coming from a pressure cylinder and regulated by a reducing valve V_R is pre-cooled in the counter-current heat exchanger G and then partly or completely liquefied in the spiral S . This spiral is placed in the condensation vessel 1 which is filled with a liquid having a suitable boiling point. The mixture of liquid and vapour is now brought through an insulated tube into the pressure

cryostat 2 where it fulfils two functions. It supplies the necessary cold in order to keep the quantity of liquid here constant, and its stirring action provides a homogeneous temperature in the liquid which boils under pressure. The gas produced by heat influx from outside and by the actual measurement leaves the system through the heat exchanger G and through the valves V_1 and V_2 . Alternatively, it is passed through a rota-meter R into the storage vessel B . The contact manometer K_M regulates a magnetic valve V_M in such a manner that the pressure over the bath is kept constant, and by suitable adjustments of the valves V_1 and V_2 pressure fluctuations are being kept as small as possible. The height of the liquid level is read on an indicator. The platinum resistance thermometer P reads the mean temperature, while possible inhomogeneities will be noted by a differential thermocouple T_C . M is the space in which measurements are carried out—and in the present case it is used for the determination of equilibria of binary gas mixtures.

The vapour leaving vessel 1 passes through the heat exchanger G , too, and since the pressure drop does not exceed 0.2 atm overpressure, any type of Dewar vessel can be used.

Any change in the volume velocity of the gases passing through the spiral S will also alter the cooling rate transmitted to the pressure cryostat. This means that according to the rate of gas flowing, the liquid level can fall, rise, or remain constant.

Since the total quantity of cold required is supplied by the condensation vessel, only this has to be refilled. A variation in the degree of filling will not influence conditions in the pressure vessel as long as the spiral S is covered with liquid.

The only condition which the liquid in the condensation vessel has to fulfil is that its boiling point, at a pressure of 1.2 atm, has to be a few degrees lower than the liquid in the cryostat at the chosen working pressure. The liquid in the cryostat must have the same composition as the gas from the pressure cylinder because, as the pressure is kept automatically constant, concentration changes would otherwise result in a variation of the temperature. This is best achieved by condensing liquid into the cryostat in the way through vessel 1, when first filling. One can, in this manner, achieve with 98 per cent pure nitrogen the same constancy of temperature as with very pure nitrogen (99.9 per cent).

The first experiments were carried out with nitrogen up to a pressure of 11 atm. Both vessels were filled with liquid

[†] Substance of a lecture delivered at a Memorial Colloquium for the late Sir Francis Simon at the Humboldt University, Berlin, 9 November 1960.

nitrogen. The mean temperature of the cryostat, at constant gas flow, could be kept constant within the accuracy of measurement ($\sim 0.1^\circ\text{K}$) for several hours, with the total variation of temperature amounting to $\pm 0.2^\circ$. Figure 2 (curve A) shows, as an example, the variation of the mean temperature ($T = 94.7^\circ\text{K}$) with time, at $p = 5$ atm. The amount of nitrogen passing per hour was 600 l. Throughout this time the liquid level in the cryostat remained constant to about ± 1 mm.

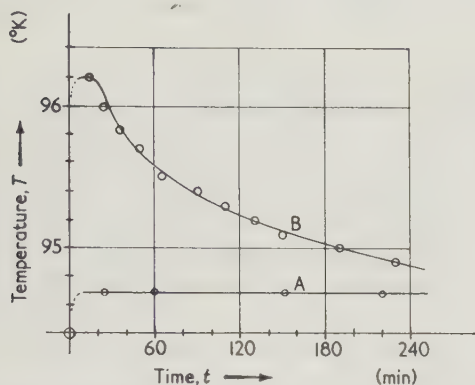


Figure 2. Change of temperature with time for nitrogen

The variations of the mean temperature are connected with the pressure variations resulting from the degree of sensitivity of the contact manometer. They can be further decreased by a more sensitive regulating mechanism. The thermocouple occasionally registered temperature differences which occurred in one direction only and which were of the same order as the total temperature variation. We think that these irregular temperature fluctuations might be diminished by appropriate changes in the construction of the apparatus.

If one wishes to change over to another temperature, the corresponding pressure has first to be adjusted with the contact manometer and then the gas flow must be regulated so that the liquid level remains constant. The necessary volume velocities for nitrogen are shown in Figure 3 in dependence on temperature.

The consumption in the condensation vessel at 3 atm (88°K) amounted to 1.4 l./hr and at 11 atm (105°K) to about 1.1 l./hr. Since the apparatus was originally planned for other purposes, the insulation of the vessel was

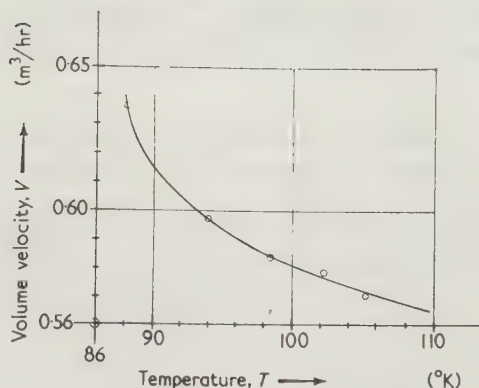


Figure 3. Gas flow for nitrogen in dependence on the temperature in the cryostat

insufficient and the zero losses (about 0.6 l./hr) are accordingly fairly high. Details will be discussed elsewhere.

When technical liquid nitrogen (about 15 per cent O_2) was used for filling the pressure vessel, together with cylinder nitrogen of about 98 per cent purity for the gas flow, the temperature did not remain constant since the oxygen concentration was changed, and only gradually approached a final value (Figure 2, curve B).

In experiments with argon, the condensation vessel was filled with oxygen. To give an example, at a working pressure of 12 atm a temperature of 120°K was reached and kept for several hours. The oxygen consumption was about 0.8 l./hr with an argon flow of 0.5 m^3 . The temperature constancy, the fluctuations, and the temperature differences recorded by the thermocouple were the same as those observed with nitrogen.

The experiments are being continued. In the region above 80°K we hope to reduce the extent of the fluctuations and to achieve some degree of automation (using condensation level detectors² for automatic adjustment of the gas flow and for the filling of the condensation vessel). Moreover, it is intended to modify the apparatus for use in the temperature region of $27\text{--}42^\circ\text{K}$ which is accessible with liquid neon.

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Letter to the Editors

The Superconductive Transition in a Transverse Field at Various Orientations for Thin Tin Films

THE variation of electrical resistance in the superconductive transition of thin tin films has been studied as a function of the orientation of a transverse field H . It has been found that the transition displacement is given by $H/\cos \alpha$, where $90-\alpha$ is the angle between the field direction and the plane of the film.

The specimens, prepared in a vacuum of $\sim 5 \times 10^{-6}$ mm Hg and deposited on mica, were thin films of tin 4 mm long, 0.15 mm wide, with thicknesses of 2,000 and 3,500 Å. Silver deposited across the ends of the tin strip enabled the use of press contacts to fasten the electrical current and potential leads. The e.m.f. developed across the strip for a current in the z direction of 1 mA (see Figure 1 (b)) was measured on a Tinsley vernier potentiometer. Magnetic fields were produced by a Helmholtz coil, mounted so that it could be rotated about the axis of the Dewar vessel.

The transition for the 2,000 Å film occurred at 3.836°K in zero magnetic field. It was noticed that for fields applied in the x direction, perpendicular to the plane of the film, the transition was reasonably sharp (~ 3 in 20 gauss for 80 per cent resistance to be restored). At 3.58°K , the critical field was about 4.5 times greater than that of a bulk tin sample. With the field in the y direction

much higher values were needed before the resistance began to rise. The transition was therefore investigated at constant temperature, while the field was rotated in the x - y plane, since it seemed that the perpendicular component of the field was the determining factor of the transition. The results for various orientations α to the x axis for the 2,000 Å film are shown in the diagram.

When $H \cos \alpha$ is plotted against $R/R_{4.2}^\circ \text{K}$ it is noted that within the experimental error all transition curves coincide. This was found to be true for all the angles measured between 0 and 75 degrees. It thus appears that it should be possible to predict the shape of the transition for any orientation of the field once one measurement has been done at a known angle. Obviously the law must eventually break down at a large angle for the observed transition to take place at $\alpha = 90$ degrees. Results similar to those on the 2,000 Å film have been obtained with the 3,500 Å film.

My thanks are due to Dr. K. Mendelssohn for his interest in this work, and to Professor M. Blackman and Dr. A. E. Curzon of Imperial College for making the tin films.

J. M. CORSAN
(1 February 1961)

The Clarendon Laboratory,
Oxford.

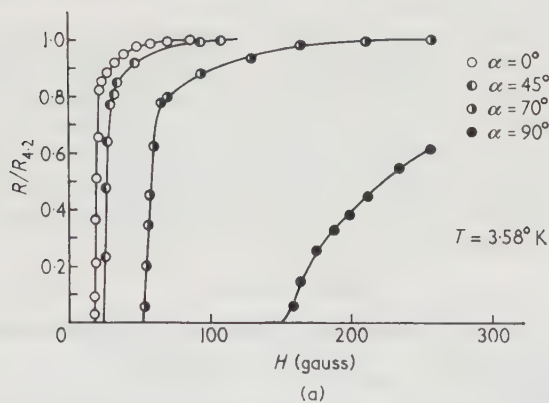


Figure 1 (a). Transition curves for a tin film at different directions of the transverse magnetic field

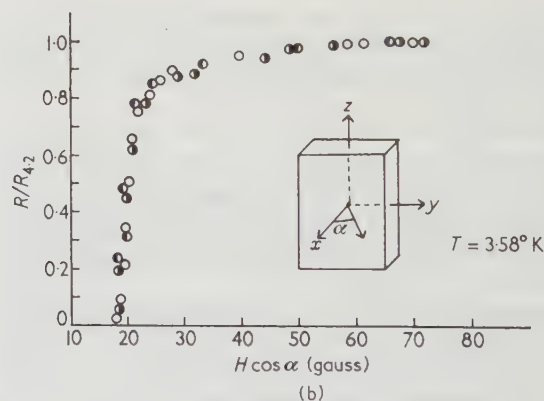


Figure 1 (b). The transitions plotted against $H \cos \alpha$

Book Reviews

Progress in Cryogenics 2. Edited by K. Mendelssohn. (Heywood, 1960) 280 pages. 63s.

The collections of review articles contained in the various 'Progress' series put out by several publishers stand on the bookshelves as a continuing reminder of one's ignorance of recent work in many of the rapidly expanding branches of physics. Occasionally we flick through the pages of a volume in the hope that there might be an article which will bring us up to date in a field in which we have an interest, but which is outside our normal range of activity. Aha! we say, this looks as if it will be interesting and we start to read. How often are our hopes dashed when one is met not with a good clear description in the English language but with jargon—so another article is put down unread.

It is a pleasure, therefore, to praise in this volume the chapter on the three level solid state maser, by E. O. Schulz-Du Bois, written in clear and intelligible English and in which the jargon, where it has to be employed, is at least explained. It is not, however, an oversimplified article. Each of the many topics which enter into maser theory, design, and experiment is carefully discussed in considerable detail. It is an excellent introduction to the subject. The chapter on low temperature bubble chambers, by N. C. Barford, is also a good businesslike description of all the important design aspects of a rapidly developing technology. The article on methods of nuclear orientation, by E. Ambler, one of the leading workers in this field, regrettably descends into jargon. It will certainly be very useful to the specialist who is already working in this subject, particularly because it contains copious references and tables, but it will prove difficult reading for the interested outsider.

Anyone who has had the privilege of hearing one of the very elegant lectures given by J. W. L. Köhler will not be disappointed by the lucid description he gives in a chapter on the Philips air liquefier. This is so persuasive in its presentation that one feels that a postage-paid order form enclosed in each volume would yield very satisfactory results to the Board of Directors at Eindhoven.

There are four other articles in the volume. One deals with the separation of deuterium by low temperature distillation, by M. P. Malkov, A. G. Zel'dovich, A. B. Fradkov, and I. B. Danilov; this describes only the work which has been done in the U.S.S.R. and makes no mention of separation experiments which are being made in other countries. There is a very erudite chapter on the 1958 helium-4 temperature scale, by H. van Dijk, in which the methods of computation and the probable errors are described in great detail. This is followed by an article on resistance thermometers for low temperatures, by C. R.

Barber, which tries to relegate what is essentially an art into a science. He describes in considerable detail the practical realization of an accurate temperature scale below 90° K with the use of platinum resistance thermometers. The remaining article is by G. H. Zenner on the storage and handling of cryogenic liquids. This is concerned for the most part with the bulk handling of liquid oxygen and useful design figures on railway tank cars are given.

There seem to be a few mistakes in the text, the outstanding one being on page 158, in which a thermometer coil is described as being wound with 50 turns per centimetre using wire which is 0.75 mm in diameter. The other errors can be quite as easily detected and amended by the alert reader.

H. M. ROSENBERG

Experimental Techniques in Low-Temperature Physics.

G. K. White. (Clarendon Press, 1959) 346 pages. 45s.

Not many practical books on science can be read for pleasure but Dr. White's book is in this class, and worthy of the bedside of any practical physicist, be his temperature low, high, 300° K, or 101° F. It is also a most useful book to have in any laboratory where helium comes in as liquid and goes out as gas.

Part I, General, deals with the production of low temperatures, the storage and transfer of liquefied gases, heat exchangers, and temperature measurement. Part II is about the research cryostat, and it manages to be advanced without being overpowering. The chapter on heat transfer is particularly lucid, and it contains a practical example of the type of heat flow calculation which ought to be done much more often than it is, during the design of the cryostat and not, as is so common, during its test runs. Part III is a collection of physical data, valuable because low temperature data are scattered and hard to come by. Many readers would like to see this collection made much more comprehensive.

The subject index is rather meagre. There are numerous references at the ends of chapters, and these may be traced back to the text by way of the author index at the end of the book. Do they have a slight European bias? The author is an Australian, and he seems to have written the book partly in Oxford and partly in Canada, so its readers may expect to have some of the best of both hemispheres.

A. R. MEETHAM

Solid State Physics: Advances in Research and Applications.
Vol. 10. Edited by F. Seitz and D. Turnbull. (Academic Press, 1960) 516 pages. \$14.50 (103s. 6d.).

In recent years there has been an ever increasing number of book series that serve as Reviews, Advances, or Progresses in selected topics. The quality and usefulness of the different series vary considerably; the semi-annual volumes of *Solid State Physics* are, however, among the best. Since 1955 ten volumes with a total of 57 articles have appeared. On the average, each volume contains one article of immediate and direct concern to cryogenics and one other that is of secondary importance or is useful for background material. The others are concerned only slightly or not at all with low temperature phenomena. The stated aims of these volumes were to be somewhat different from those of similar publishing ventures; that is, the series was to serve as 'an up-to-date treatise on solid state science' with the basic reviews covered 'in about a dozen volumes'. The series does not seem to have accomplished the goal as yet, mainly because of the number of articles on narrowly restricted topics. More broad surveys would have helped to attain the objects more rapidly, and would have been appreciated, at least by this reviewer. Nevertheless, the books have been extremely valuable for those general surveys that did appear and for the many well written articles on specialized topics.

Volume 10 is better balanced in content than are several of the volumes before it, having a fairly even balance of both theoretical and experimental topics, and of both specialized and more general reviews. The first article, on positron annihilation by P. R. Wallace, describes the effect and how it may give information, unfortunately rather limited, on the electronic structure of various solids and liquids. The next article, on diffusion in metals by D. Lazarus, contains a good general discussion of the subject, both theoretical and experimental, and serves admirably as an up-to-date basic review. The third article, on wave functions for colour centres by B. S. Gourary and F. J. Adrian, confines itself to a highly restricted, though active, subject: wave functions for *electron-excess* colour centres in *alkali halide* crystals of the *NaCl* structure. The fourth article, on theory of dislocations by R. de Wit, summarizes the continuum approach, particularly Kröner's field equation formulation, to the theory of well separated, stationary dislocations in isotropic media.

The last and longest (206 pp.) article in the volume, and the one most important to cryogenics, is on theoretical aspects of superconductivity by the late M. R. Schafroth. This lengthy review is divided into two parts, phenomenology and microscopic theory.

The phenomenology part is extensive and self-contained: it does not depend on reference to previous books on the subject, but in fact covers much of the same material that is already available elsewhere. This detailed review is only justified because of the different approach used to describe the familiar effects. The thermodynamics, Meissner effect and electrodynamics of superconductors are described in terms of *general* phenomenologies, the Lon-

don theory being only one special, though important, example.

The part on microscopic theory is more valuable since it summarizes more recent research, material not covered generally in other books. As an introduction there are very good chapters on general concepts of microscopic theories and on the older single electron theories. The last chapter describes recent pair correlation theories, particularly those of Bogoljubov and Bardeen-Cooper-Schrieffer. The article is completed by an extensive bibliography. The report by Schafroth is an example of a broad basic review at its best.

Volume 10 of *Solid State Physics*, in fact the whole series, should be in the library of every cryogenics laboratory and physics department. Individual purchase of Volume 10 by a person working in cryogenics would be justified if he were following critically the developments in superconductivity. Individual purchase of future volumes would be more rewarding if each one were restricted to one or two general topics, with a broad basic review in each followed by several specialized articles.

R. L. POWELL

Cryogenic Engineering. R. B. Scott. (Van Nostrand, 1959) 368 pages. 42s. (\$5.60).

In 1952, the National Bureau of Standards, with financial help from the Atomic Energy Commission, established a laboratory at Boulder, Colorado, for research and development into cryogenic engineering. This laboratory has played a leading part in the development of cryogenics during the last eight years, not least by the organizing of an annual cryogenic engineering conference.

The Chief of this laboratory (and incidentally the American editor of *CRYOGENICS*) has written an authoritative book on cryogenic engineering which was so successfully received that it was reprinted six months after publication. Russell Scott makes it clear that he has received much help from his staff and it is interesting to find a book, which it is hoped will become a standard textbook, containing so much original information.

Principles are treated adequately but briefly and the author soon gets the reader down to the practical applications of cryogenics and the practical solutions of the manifold problems that arise. So many potential applications of cryogenics are arising and so many new workers are coming into this field that good textbooks are becoming a necessity.

The layout of the book is very pleasing. Chapters are well divided by clear sub-headings and the diagrams and illustrations are of a high quality.

Scientists in Europe and the Commonwealth, as well as in the U.S.A., will be grateful to the Bureau of Standards for the pioneering work they have done and are still doing, and to Russell Scott for this very readable textbook.

N. BOOTH

Advances in Cryogenic Engineering. Vols. 1-5. Edited by K. D. Timmerhaus. (Plenum Press, 1960).†

There is no need to labour in these pages the rapidly growing importance of cryogenic engineering. The years after World War II have not only seen the great engineering effort connected with the rocket programme but quite a number of other, mostly unconnected, developments, particularly in the temperature regions of liquid hydrogen and liquid helium. In order to fill the demand for scientific and technical data required for these programmes and to gain more experience in the handling of liquefied gases, the U.S. National Bureau of Standards in conjunction with the Atomic Energy Commission established a special laboratory at Boulder, Colorado. The suggestion for establishing such a research centre came in 1949 from members of the Los Alamos Scientific Laboratory and, under the guidance of the Chief of the Bureau's Heat and Power Division, Dr. F. G. Brickwedde, plans were immediately drawn up and put into effect. Building was started in 1951 and the liquefier hall as well as the laboratories were ready a year later.

Operation was in full swing in 1954 when the new laboratory became a separate Division of the Bureau of Standards with R. B. Scott as its chief. Scott thought not only in terms of a technical laboratory but also in those of a centre of research and information to which other low temperature workers in the United States, or indeed in the world, could turn. It was therefore one of his first actions to hold a conference on cryogenic engineering aspects at the new laboratory in September, 1954.

This was the first of the six conferences of this kind which have been held so far. The second meeting was held in September, 1956, but after this it was felt that two-year intervals were too long and the subsequent conferences were held annually. The second and third also took place at Boulder, but M.I.T. was chosen for the fourth and Berkeley for the fifth. The sixth conference, in August, 1960, returned to Boulder. The speakers at these conferences submit shortened versions of their lectures at the time of

the meeting and these have been edited annually by the Conference Secretary, Professor K. D. Timmerhaus of the University of Colorado. He has been untiring and eminently successful in preparing, each year, a complete record of the conference, which has been the standby for all those working in the field. These reports were published in limited editions by the Cryogenic Engineering Conference, aided by financial support from industry.

Lately, with the large expansion of low temperature work, there has been a great demand for back numbers of the Conference Report and it also became clear that in future the strictly limited editions would be quite insufficient. The decision of Plenum Press not only to publish the further reports but also to furnish bound copies of the earlier ones is therefore most welcome. They are to be congratulated on having made a most efficient job of it. The first four volumes, with an uneven right-hand margin in the printing, have the flavour of circulated reports, but Volume 5 is a neatly finished book. A certain number of misprints in the earlier volumes are, under these circumstances, readily forgiven and do not detract from the value of the issues.

It would be a hopeless task trying to summarize the contents of the five volumes; they are a full record of the progress of cryogenic engineering. They also show how, from a relatively small nucleus centred on the Boulder Laboratory, the field has spread. The later volumes, in particular, emphasize the international co-operation in low temperature engineering which the conferences have inspired. For all those working seriously in the field, these volumes will be indispensable as a source of reference and information.

K. MENDELSSOHN

†Note. Price per volume: \$13.50 to U.S. buyers; \$15.00 to others.

Volume 5: Price to members \$6.50.

Volumes 1-4 in set: \$35.00 (U.S.) and \$40.00 (others).

EDITORIAL NOTE

CRYOGENICS offers congratulations to one of its Advisory Editors, Professor Rudolf Plank of Karlsruhe, on the occasion of his 75th birthday on 6 March 1961. Professor Plank, one of the pioneers of cryogenic engineering, studied at Kiev, St. Petersburg, and Dresden, and was a pupil of Richard Mollier. He retired in 1954 from his professorship at the Technische Hochschule at Karlsruhe where in 1926 he had founded a research institute for cryogenic technology. Internationally and in Germany he has held a number of high offices in which he has served the subject of cryogenics. Among the many honours he has received are the Kamerlingh Onnes and the Linde Memorial Medals.

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